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DEVELOPMENT OF AN INTEGRATED, ZERO-G PNEUMATIC
TRANSPORTER/ROTATING-PADDLE INCINERATOR/CATALYTIC AFTERBURNER
SUBSYSTEM FOR PROCESSING HUMAN WASTES
ON BOARD SPACECRAFT

Component Performance Summary Report

By S. F. Fields, L. J. Labak, and R. J. Honegger

April 1974

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Prepared under Contract No. NAS 2-6386 by

GENERAL AMERICAN RESEARCH DIVISION

GENERAL AMERICAN TRANSPORTATION CORPORATION

Niles, Illinois

for

AMES RESEARCH CENTER

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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FOREWORD

This report summarizes the results of the component development for an integrated, zero-g dry incineration subsystem for processing human wastes on board spacecraft. The work was conducted for the Ames Research Center of the National Aeronautics and Space Administration, under Task I of Contract No. NAS 2-6386, by the General American Research Division of the General American Transportation Corporation during the period October 1973 to April 1974 (GARD Project No. 1523).

The NASA Technical Monitor was Dr. Phillip D. Quattrone, Chief of the Environmental Control Research Branch; the program was comonitored by Dr. John Manning of Stanford University under a NASA University Consortium. Personnel in the Environmental Controls Systems Department at GARD performed the activities: Mr. Philip A. Saigh served as Program Manager and Dr. Stephen F. Fields served as Project Engineer. Messrs. Lawrence J. Labak and Robert J. Honegger performed the designing, fabricating, and testing of the various components.

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ABSTRACT

A study was performed to develop four components -- a particle size reduction mechanism, a pneumatic waste transport system, a rotating-paddle incinerator, and a catalytic afterburner -- which are to be integrated into a six-man, zero-g subsystem for processing human wastes on board spacecraft. The study included the development of different concepts or functions, the establishment of operational specifications, and a critical evaluation for each of the four components.

A series of laboratory tests was run, and a baseline subsystem design was established. The study was concluded by writing an operational specification in preparation for detailed design and testing of this baseline subsystem.

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Section 1

INTRODUCTION AND SUMMARY

1.1 Introduction

In the overall operation of manned spacecraft, proper management of wastes is essential to sustaining life within the closed spacecraft environment. Several factors influence the selection of a spacecraft waste management system, but foremost among these are crew safety and, in particular, system and end-product sterility. Also, the waste management system must be crew-acceptable both with respect to operation and man-system contact; it should be self-regulating and easily controllable with a minimum of crew participation, designed such that minor repairs or corrections can be readily carried out, and based on well-established physical, chemical, and biological principles. Finally, the system must be reliable and its use psychologically acceptable.

Of the various systems that have been contemplated for treating spacecraft wastes, the dry incineration system appears to be most suitable for the following reasons:

1. All end products -- water, ash, and gases -- are safe and permanently sterile, with no capability to provide or support biological growth or to support combustion.
2. All wastes from the bodily metabolic and elimination processes and from spacecraft housekeeping can be transformed to usable and/or storable products that are psychologically acceptable with no odor or disagreeable appearance. Product storage for indefinite periods is possible, and accidental leakage or spillage at any time into the cabin presents minimal safety or health hazards to crew members.

3. The basic dry incineration process is simple in principle and safe, with operations occurring at essentially ambient pressure and controlled temperatures up to 650°C (1200°F).
4. The weight of the solid ash after dry incineration is 5-10% of the original weight of the wet wastes. Product water is of a purity suitable, if needed, for recycling to the basic spacecraft water recovery system. Also, product gases -- oxygen, nitrogen, and carbon dioxide -- are suitable for direct return to the cabin atmosphere for partial make-up of overboard leakage or for storage and possible use in spacecraft control and/or propulsion systems.

The need for power to heat the incinerator, for an oxidant gas, and for a mechanically operating system appear to be compensated for by the above desirable system characteristics.

Since the dry incineration process produces sterile, innocuous, and conveniently managed end products, and since it lends itself to the development of a safe, esthetically acceptable system, it has been subjected to considerable investigation by the General American Research Division. Basic concepts and principles of human waste incineration for spacecraft use have been defined and a prototype incineration unit has been fabricated and successfully tested.

Under a previous NASA Contract, No. NAS 2-4438 (GARD Project 1437), testing and evaluation were conducted on microwave treatment and incineration of human feces, with characterization of the effluent products. Subsequently, under Contract No. NAS 2-5442 (GARD Project 1493), an experimental study was performed on the dry incineration of human fecal matter and urine distillate residue, and a prototype hardware incinerator was constructed and tested. The

effects on dry incineration of operating pressure, oxygen concentration, power input, sample configuration, and catalytic oxidation of gaseous products were evaluated; and the concentration, identity, and sterility of liquid, gaseous, and solid end products were established*.

The four-man prototype, dry incineration system developed under Contract No. NAS 2-5442 did not require manual handling of the wastes, but it did entail manual handling of a waste-filled incinerator/canister. Since no manual handling of any type was desired, Contract No. NAS 2-6386 was awarded for the development of an automatic, zero-g waste transport subsystem that would transfer human and nonhuman wastes from a collection site to an incineration unit on board spacecraft. Concurrently, the need arose for greater system capacity to accommodate six men instead of four.

Contract No. NAS 2-6386 (GARD Project 1523) initially consisted of seven phases (A-G) and included development and in-depth testing of additional components and subsystems to provide a totally integrated waste management system. A study of the autoclave method of waste treatment was included in the program, since this technique appeared to be applicable to short-duration space flights.

The waste transport system developed early in the program utilized pneumatic drag to collect and transfer waste materials from a commode to an incineration unit. Since pneumatic waste transport was being utilized in other waste management systems for spacecraft, and since dry incineration with catalytic afterburning was a viable technique for treating human wastes on board spacecraft, the need existed to adequately develop and characterize, in detail, the technologies associated with these processes. To accomplish this objective, the activities under Phases A-G were modified in October 1973, and the program was divided into four major tasks:

*See NASA CR-114279

Task I -- Development of Subsystem Components

Task II -- Development of an Integrated Subsystem

Task III -- Evaluation of an Autoclave Waste Management System

Task IV -- Documentation

Task I was concerned with the technology development and prototype hardware design and testing of a particle size reduction mechanism, a pneumatic waste transport system, a rotating-paddle incinerator, and a catalytic afterburner for processing human wastes on board spacecraft. This report includes a summary of all activities performed under this task.

The activities to be performed under Task II will be concerned with the technology characterization and prototype hardware development of an integrated waste management subsystem to provide a suitable basis for flight system trade-off studies, flight hardware design, etc., including the effects of zero-gravity operation; this subsystem will be formed by integrating the four major components developed and characterized in Task I. This report includes an operational specification and a basic configuration drawing for this integrated subsystem. The final design and results of testing of this subsystem will be fully documented in a separate report at the end of Task II.

The objectives of Task III are to:

1. Adequately evaluate a waste management system based on the autoclaving method of sterilization,
2. Analyze the system to determine optimum design requirements, and
3. Compare the optimized autoclave system with other spacecraft waste management systems.

The results of this task will also be summarized in a separate report.

1.2 Summary

Pneumatic Waste Transport System - Pneumatic drag of whole waste material from a collection site (commode) to a rotating-paddle incinerator through a 6.4-cm (2-1/2-in) ID, paper-lined transport tube was found to be the most effective method of waste transport and has been selected for use in the integrated subsystem. The paper liner is specially treated to repel moisture and is designed to tear easily; it is released for incineration after each commode use. Of the nineteen different liners tested, four met all required criteria, and six others appeared suitable for use, if necessary. These papers have either a wax coating or a thin lamination of polyethylene, the former being more easily torn and, thus, more desirable in terms of processing after use.

Particle Size Reduction Mechanism - Several particulate size reduction mechanisms were conceived and evaluated; the most promising concepts were then fabricated and tested with simulated human wastes and toilet tissue. The mechanism selected for inclusion in the integrated subsystem consists of a permanent shear bar attached to the inner surface of the incinerator inlet cover plate and located on a chord between the waste transport tube inlet and the rotating drive shaft. Rubbing of the rotating paddle blades against this shear bar during waste loading of the incinerator results in adequate shearing and distribution of toilet tissue without significant accumulation of paper at the inlet tube. Simulated human wastes and the transport tube paper liner are also adequately processed by this arrangement. Upon completion of waste loading, the paddle blade configuration is manually indexed to prevent shear bar contact during the remainder of the processing cycle.

Rotating-Paddle Incinerator - Five incineration tests were conducted with a rotating-paddle incinerator prior to selecting the optimum configuration for the integrated subsystem. The configuration selected consists of four paddle

blades mounted 90° apart on a central rotating drive shaft/exhaust tube and confined within an outer stationary shell. The paddles come to within approximately 2.5 cm (1 in) of the shell to provide an annular space for retention of the wastes by the centrifugal force field developed by the rotating paddles. "Finger" extensions on the paddles rake through the waste mass to prevent adhesion on the shell and to continually expose the wastes to thermal processing and oxidation. A minimum paddle blade rotational speed of 300 rpm has been found necessary to prevent solid and liquid wastes from entering the central rotating exhaust tube.

Other significant design features include:

1. A plug-seal to prevent wastes from re-entering the transport tube after waste loading,
2. A labyrinth drive shaft seal supplied with inert gas to prevent wastes and generated gases from entering the bearing housing,
3. Controlled introduction of oxygen through the bearing housing and labyrinth seal for the final combustion phase of waste processing, and
4. Allowance for reverse flow evacuation of final ash to an ash collector after waste processing is complete.

Other design features are discussed in Section 5 of this report, entitled "BASELINE INTEGRATED WASTE INCINERATION SUBSYSTEM".

Catalytic Afterburner - The catalytic afterburner fabricated and tested in the previous program (NASA Contract No. NAS 2-5442, GARD Project 1493) was found to be suitable for use in the current integrated subsystem without the need for significant design modifications.

Section 2

PRELIMINARY INVESTIGATIONS

Prior to fabrication and testing, operational specifications were prepared for each of the four major components under evaluation: particle size reduction mechanism, pneumatic waste transport system, rotating-paddle incinerator, and catalytic oxidation unit. These specifications defined the purpose, mode of operation, location, configuration, performance requirements, operating constraints, design constraints, and acceptability requirements for each component. The specifications are presented in Tables I-IV. Acceptability requirements are not shown in the tables since these requirements were the same for all four components:

- Must provide simplicity of use
- Must provide user safety
- Must not be offensive to sight, touch, smell, or hearing
- Must provide user comfort

2.1 Particle Size Reduction Mechanism

The purpose of the particle size reduction mechanism is to reduce the size of whole human wastes and toilet tissue to facilitate their incineration. Possible locations for the reduction mechanism include the commode, transport tube, and incinerator. The main requirements of the mechanism are that it accept all waste materials and adequately reduce their size without physically plugging, that it not drive the waste materials in the wrong direction, and that it can be easily cleaned or kept clean during use.

Based on the specifications, eight size reduction configurations were conceived and thoroughly evaluated. The evaluation involved rating of the candidate concepts with respect to such parameters as power, weight,

Table I OPERATIONAL SPECIFICATIONS: PARTICLE SIZE REDUCTION MECHANISM

ITEM	SPECIFICATIONS
Purpose	To reduce the size of whole human feces and toilet tissue to facilitate their transport to an incinerator and their subsequent incineration.
Mode of Operation	Reduce particle size by cutting or cleavage, or by extrusion from larger to smaller cross-section.
Location	Will be located in commode, transport tube, or incinerator. Location will be based upon mode of operation selected.
Configuration	Size of reducer will be larger than maximum particle size anticipated, will fit within either commode, transporter, or incinerator. Shape will be governed by location and position in transporter or incinerator.
Performance Requirements	<p>Must accept whole fecal matter and reduce their size to that which can be readily pneumatically transported through the transport tube and accepted by the rotating paddle incinerator.</p> <p>Must be easily cleaned after use or kept clean during use.</p> <p>Must not drive wastes back up toward commode.</p> <p>Operation must not be significantly changed upon impact with wastes.</p>
Operating Constraints	<p>Must not create large pressure drop of transport gas.</p> <p>Must operate only during commode use.</p>
Design Constraints	<p>Must fit within commode, transport tube, or incinerator, as selected.</p> <p>Must be constructed of materials compatible with anticipated wastes and with location.</p> <p>Power required to drive motor must be minimum feasible.</p>

Table II OPERATIONAL SPECIFICATIONS: PNEUMATIC WASTE TRANSPORT SYSTEM

ITEM	SPECIFICATIONS
Purpose	To pneumatically transport human feces, toilet tissue, liquids, and gases from a collection site (commode) to an incineration unit. The wastes may be whole or partially reduced in size.
Mode of Operation	Pneumatic transport of wastes imparted by a blower located downstream of the system.
Location	Between commode and incinerator -- physically connects commode to incinerator.
Configuration	Tubular -- Minimum length of 30.5 cm (12 in). Inside diameter dependent upon maximum size of waste particles -- minimum I.D. of 6.4 cm (2-1/2 in) for whole wastes, 2.5 cm (1 in) for reduced wastes.
Performance Requirements	Must not physically plug with wastes. Must not collect isolated stray waste particles. Must remain clean or be easily cleaned.
Operating Constraints	Pneumatic air flow rate must be minimum feasible. Air flow must entrain all waste particles and transport them to incinerator with no build-up of back pressure. Must create slight negative pressure at commode for odor control. Must operate between commode at ambient temperature and incinerator at 650°C (1200°F).
Design Constraints	Must be constructed of materials compatible with anticipated wastes; Hastelloy-X superalloy is required at incinerator end. Power required to drive main blower and ancillary components must be minimum feasible.

Table III OPERATIONAL SPECIFICATIONS: ROTATING-PADDLE INCINERATOR

ITEM	SPECIFICATIONS
Purpose	To accept incoming solid and liquid wastes from pneumatic transporter and to convert these wastes into sterile vapors, gases, and ash.
Mode of Operation	<p>Wastes are incinerated via external electrical resistance heaters and oxygen feed for combustion.</p> <p>Process takes place in three steps: boil-off of volatiles and water from ambient temperature to 100°C (212°F), pyrolysis (thermal decomposition) in the absence of oxygen from 100°C to 540°C (212°F to 1000°F), and final combustion of carbonaceous residue with oxygen from 540°C to 650°C (1000°F to 1200°F).</p> <p>Wastes are retained within incinerator during zero-gravity operation through action of an artificial gravitational field by a rotating paddle arrangement within the incinerator with all gases and vapors discharged from central axis to a catalytic afterburner for further processing.</p>
Location	Near commode to reduce size of transport mechanism.
Configuration	<p>Cylindrical with internal rotating paddles.</p> <p>Drive shaft for paddles common with vapor and gas exhaust tube.</p> <p>Exhaust tube fitted with large diameter holes covered with mesh material to facilitate gas removal without loss of solids or liquids.</p> <p>Transport tube inlet located opposite exhaust tube discharge.</p> <p>Volume to accommodate wastes produced by six men.</p> <p>Electric resistance heaters around O.D.</p>
Performance Requirements	<p>Must confine all liquids and solids within annular space between inside wall and rotating paddles.</p> <p>Must completely sterilize all waste particles.</p> <p>Must provide for complete incineration of all waste particles.</p> <p>Must accept pneumatic air flow without creating turbulent conditions or large pressure drops.</p>
Operating Constraints	<p>Must operate between ambient temperature and 650°C (1200°F).</p> <p>Must exhaust all generated gases and vapors to catalytic afterburner.</p> <p>Must not drive vapors back up transport tube to commode.</p>
Design Constraints	<p>Must be constructed of Hastelloy-X superalloy material for corrosion resistance.</p> <p>Must contain suitable seals to prevent escape of generated gases and vapors.</p> <p>Power for rotating paddles must be minimum feasible.</p> <p>Must be insulated to prevent excessive heat loss.</p>

Table IV OPERATIONAL SPECIFICATIONS: CATALYTIC OXIDATION UNIT

ITEM	SPECIFICATIONS
Purpose	To accept effluent gases and vapors from incinerator and to convert any unoxidized materials to oxidized state for discharge.
Mode of Operation	Catalytic oxidation at 370-480°C (700-900°F) with oxygen feed.
Location	Immediately downstream of incinerator.
Configuration	Cylindrical with influent and effluent tubes located at opposite ends. Oxygen feed tube located near vapor inlet. Electrical resistance heaters around O.D.
Performance Requirements	Must oxidize all unoxidized materials. Must physically filter entrained particulates. Must provide sterilization of low-temperature volatiles and water vapor.
Operating Constraints	Must operate continuously at 370-480°C (700-900°F). Must accommodate generated gas and vapor flow without large pressure drops. Must prevent any short-circuiting of unoxidized materials.
Design Constraints	Must be constructed of Hastelloy-X superalloy material. Must be located near incinerator to minimize interconnecting piping. Must be insulated to prevent excessive heat losses. Must contain a suitable high-temperature oxidation catalyst which remains unaffected in both reducing and oxidizing atmospheres.

cleanliness of operation, complexity, ease of system integration, size, and flow restriction. A weighted, numerical rating scale was assigned to the parameters, and an overall score was obtained for each concept. The resulting evaluation was put in matrix form to provide a meaningful basis for comparatively evaluating the candidate concepts; this matrix is presented in Table V.

According to Table V, the highest rated concept involves use of rotating paddle blades within the incinerator to cut the wastes against a stationary shear bar or against the wastes themselves. Since this arrangement is located within the incinerator, the transport tube must be sized to accommodate whole waste materials. The second highest rated concept involves two versions of a rotating wire slicer located within the transport tube. The paddle blade cutter and wire slicer concepts were thoroughly tested, and the results are presented in Section 3 - TEST RESULTS; none of the other concepts in Table V was tested.

2.2 Pneumatic Waste Transport System

The purpose of the pneumatic waste transport system is to transport human feces, toilet tissue, liquids, and gases from a collection site (commode) to a rotating-paddle incineration unit; transport is achieved by pneumatic drag on the wastes created by a blower located downstream of the system. This component physically connects the commode to the incinerator. The main requirements of the transport system are that it not physically plug with waste materials, that it remain clean during use or be easily cleaned, and that it not allow the collection of stray waste particles.

An evaluation matrix was prepared for this component; however, it was developed primarily to establish design constraints and to identify potential problem areas rather than to evaluate significantly different concepts. Key elements in the evaluation included complexity, system integration, pressure

Table V PARTICLE SIZE REDUCTION MECHANISM

TYPE	MODE OF OPERATION	SYSTEM COMPONENTS	LOCATION	HORSE POWER	COMPLEXITY	WEIGHT	CLEANING TECHNIQUE	SUBSYSTEM INTEGRATION	SYSTEM DIMENSIONS	PHYSICAL FLOW RESTRICTIONS	TOTAL RATING
Jet Shear	2 or 4 opposing pulsed air jets shear bolus at anus; may be angled downward; probably will not shear paper	Nozzles (2 or 4) Pulser Piping Pressure gauge Storage tank (accumulator) Regulator, Compressor with motor	Within transport tube or at incinerator inlet	0.5 (compressor) 37	Needs pulser 18	High due to compressor and piping 6	None 15	Simple, but may dirty tube 9	Small (except for compressor accumulator, and piping) 1	Low 14	100
Paddle Blades	Rotating paddles within incinerator shear wastes against stationary block or incoming wastes themselves	Stationary shear bar Motor speed control Addtl. cutting blades	Within incinerator	0.3 45	Simple 22	Negligible 15	Clean tube 12	Simple, but may need larger transport tube 8	Negligible 15	Low 13	130
Blender	Rotating pitched blades; no fixed cutters; creates high turbulence and can propel wastes down tube	Cutting blades Motor w/housing Mounting Bearings (seals) Housing for blades Control (motor)	Within transport tube	0.7 (Intermittent) 25	Moderate; Needs H ₂ O seal 12	Moderate 13	Complex 9	Complex 5	Moderate/Low 13	Moderate 9	86
Shredder	Rotating blades shear wastes against fixed slots; can create vacuum due to configuration and thus self-feeds.	Cutting blades Motor w/housing Mounting Bearings (seals) Housing for blades Control (motor) Fixed cutting block	Within transport tube	1.0 (Intermittent) 17	Moderate 6	Moderate/High 8	Complex 5	Complex 5	Moderate/Low 11	Moderate 9	61
Macerator	Rotating cutters shear wastes against fixed cutting blocks with narrow passages between fixed blocks; may cause flow restriction; requires large head to move wastes	Rotary cutting blades Stationary cutting block Motor w/housing Bearings (seals) Forced feed mechanism	Within transport tube	1.0 (Intermittent) 17	High 4	Moderate/High 8	Poor 1	Complex 5	Moderate/Low 11	High 2	48
Extruder	Compresses wastes into smaller volume for easy entry into incinerator; non-self-cleaning; requires positive feed mechanism	Screw or piston Motor w/housing Feed hopper Air by-pass Bearings (seals)	Within transport tube	1.0 (Intermittent) 17	High 2	Moderate/High 6	Poor 1	Complex 3	Moderate 8	High 1	38
Guillotine	Oscillating double-edge blade slices wastes across tube diameter; may require flush for cleaning blade guide	Cutting knife Stationary cutting block Waste feed hopper Seal Solenoids or double-acting piston	Within transport tube	0.5 37	Moderate 6	Moderate 12	Complex 7	Complex 5	Moderate/Low 12	Moderate 10	89
Wire Slicer	Moving rigid wire slices through wastes across tube diameter; maybe eggbeater type or horizontal cutting wire across fixed cutting wire self-cleaning via shear at wall or at fixed blades	Wire assembly Motor w/housing Bearings (seals) Possible gear arrgmt.	Within transport tube	0.3 43	Moderate/Low 14	Low 14	Clean tube 11	Fairly Simple 7	Low 14	Low 12	115
RATING SCALE				50W 10 1500W: 1	Low: 10 High: 1	1-lb: 10 50-lb: 1	None: 10 Very dif: 1	Simple: 10 Very complex: 1	0-ft ³ : 10 1-ft ³ : 1	None: 10 Closed Tube: 1	---
WEIGHTED FACTOR				5.0	2.5	1.5	1.5	1.0	1.5	1.5	---
MAXIMUM RATING				50	25	15	15	10	15	15	145

drop, energy requirement, dimensions, cleaning technique, rinse water requirement, flow rate, and aesthetics. The matrix is presented in Table VI.

Three of the transport arrangements listed in the matrix were tested for concept feasibility, and these results are presented in Section 3. The three concepts tested were the "blower and liner", "blower and ultrasonic tube", and "blower and water-rinsed porous wall tube". Although the other arrangements, in some cases, had a better rating for complexity and/or system integration, other elements in the evaluation led to their elimination from further study.

2.3 Rotating-Paddle Incinerator

The purpose of the rotating-paddle incinerator is to accept incoming solid and liquid wastes from the pneumatic transporter and to thermally convert these wastes into sterile vapor, gases, and inorganic ash. The main requirements of this component are that it confine all liquids and solids and prevent their escape through the exhaust tube, that it completely sterilize all waste particles, and that it accept the pneumatic transport air flow without creating turbulent conditions or large pressure drops.

An evaluation matrix was also prepared for this component and, like the matrix for the pneumatic waste transporter, was developed primarily to establish design constraints and to identify problem areas. However, unlike the previous two matrices which evaluated different concepts or configurations, the matrix for the rotating-paddle incinerator was prepared simply as an evaluation of the various incinerator functions, including anticipated problem areas; possible solutions to these problems were also formulated for investigation later in the program. The matrix is presented in Table VII.

Table VI PNEUMATIC WASTE TRANSPORTER

TYPE	MODE OF OPERATION	SYSTEM COMPONENTS	COMPLEXITY	SYSTEM INTEGRATION	PRESSURE DROP* (IN H ₂ O)	ENERGY** (WATT-HR/DAY)	SYSTEM DIMENSIONS		CLEANING TECHNIQUE	ADDITIONAL INCIN. POWER REQD DUE TO RINSE (BTU)	TRANSPORT AIR FLOW RATE (CFM)	AESTHETICS
							Height (in.)	O.D. (in.)				
Blower Only	Blower downstream of incinerator creates suction at commode; imparts pneumatic drag to waste particles	Blower	Low 9	Simple 9	1	75	12	3	Swab [†] or spray rinse (200 cc/use)	2650	<40	Acceptable except for possible use of swab
Blower and Pneumatic Tubes	Particle drag with air film to protect wall; requires high air pressure in annulus around pneumatic tubes	Blower Compressor Storage tank (accumulator) Tube annulus	High/Moderate 3	Moderate 6	1	.75(blower) + 150(comp) = 225	12	4 + 1 cu. ft.	Swab or spray rinse (100 cc/every other use)	660	<40	Acceptable except for possible use of swab
Blower and Sealed Carrier	Containerization of wastes with pneumatic transport of filled container (carrier) to incinerator	Blower Carriers & storage Carrier loader Carrier closer Carrier holder & release mechanism	High 1	Complex 3	Waste flow: 4 Carrier flow: 7 (Momentary)	75	15	3 + 1 cu. ft.	Swab or spray rinse (200 cc/day)	440	<10	Acceptable except for possible manual insertion of carrier
Blower and Liner	Particle drag with liner (paper or plastic) to protect transport tube walls	Blower Liners & storage Liner loader Liner holder & release mechanism	High/Moderate 3	Complex 4	Waste flow: 1 Liner flow: 7 (Momentary)	75	12	3 + 1 cu. ft.	Swab or spray rinse (200 cc/day - only for off-design conditions)	440 (Only for off-design conditions)	<40	Acceptable except for possible manual insertion of liner
Blower and Heated Tube	Particle drag; incinerate stray particles on tube	Blower Possible heating elements around tube Insulation Special commode lid	Moderate/Low 7	Moderate/Simple 8	1	75	4	9††	Spray rinse (100 cc/day)	220	<40	Acceptable except for close proximity of incinerator to commode
Blower and Ultrasonic Tube	Particle drag-vibrate transport tube walls with ultrasound to keep walls clean	Blower Ultrasound generator Possible fluid medium on outside of tube to transmit sound waves	Moderate/Low 7	Moderate/Simple 8	1	75(blower) + 50(ultrasonic gen.) = 125	12	3.5 + 0.3 cu. ft.	Spray rinse (100 cc/day)	220	<40	Acceptable except for possible noise from generator
Blower and Water-Rinsed Porous Wall Tube	Particle drag; water in annulus creates water film on I.D. of porous wall tube (continuous bleed of water)	Blower Tube annulus Water pump & storage tank	Moderate 5	Moderate/Complex 5	1	80	12	4 + 0.3 cu. ft.	Continuous water sweat (15 cc/use or 100 cc/day) or swab	220	<40	Generally acceptable
RATING SCALE			Low: 10 High: 1	Simple: 10 Complex: 1								

* From commode outlet to incinerator inlet (no reducing mechanism)

† With disposable wiper

** Based on 6 men, 5 minutes each

†† Due to insulation

Table VII ROTATING-PADDLE INCINERATOR

INCINERATOR SYSTEM FUNCTIONS		FUNCTION DESCRIPTION	MODE OF OPERATION	COMPONENTS		POTENTIAL PROBLEM AREAS	POSSIBLE SOLUTIONS TO PROBLEMS
				INCINERATOR	ANCILLARY		
Waste Feed Accommodation		To accept and distribute wastes uniformly in annular volume with no inlet blockage	Sufficient transport air velocity to carry wastes into incinerator; centrifugal force field used to obtain axial distribution	1)Paddle blades 2)Inlet transport tube interface	1)Motor 2)Speed reducer	1)Waste build-up along one side of feed tube at incinerator inlet 2)Feed tube diameter and location dictates incinerator diameter	Use of protective liner within feed tube to protect transport tube wall from expected waste build-up
Particle Size Reduction		To reduce size of waste feed to facilitate waste distribution within incinerator	Shearing of wastes at inlet by using modified paddle blades with transport air on	"Modified" paddle blades	1)Motor 2)Speed reducer	Not able to shear paper causing wrap-around cutter blades and/or paddle blades leading to blockage	1)Minimize clearance between shear blades and stationary cutting block 2)Possible higher rotational speed 3)Supplementary particle size reducer prior to inlet
Gas and Liquid/Solids Separation		To maintain liquids and solids in annular volume with axial removal of lightweight gases and vapors	Rotation of paddle blades for centrifugal effect	1)Paddle blades 2)Mesh barrier 3)Drive tube exhaust 4)Air seals	1)Motor 2)Speed reducer	1)Build up of solids on mesh 2)Abrasion at endplate mesh causing leakage out exhaust tube	1)Higher rotational speed 2)Additional paddle blades 3)Spring face seal on end-plate instead of mesh
Annular Containment of Liquids and Solids							
INCINERATOR OPERATION	Boil-Off	Evaporation of water & low boiling volatiles from wastes in the absence of oxygen	1)Heating with electrical heaters 2)Controlled heat transfer rate 3)Generated gas and vapor removal 4)Paddle blade rotation	1)Electrical wall heaters 2)Temperature sensor	1)Temperature controller 2)Thermal insulation	NONE	— — —
	Pyrolysis	Thermal cracking and decomposition of hydrocarbons in the absence of oxygen				Introduction of O ₂ via coolant gas seal may cause detonation of pyrolysis gases	Use inert gas (e.g., N ₂) for gas seal and coolant
	Final Combustion	Oxidation of carbonaceous pyrolysis residue				1)Generated gas removal 2)Paddle blade rotation 3)Controlled O ₂ flow to contact pyrolyzed residue at 1000°F; heaters off; high-temperature safety cut-off	1)Temperature sensor 2)O ₂ supply header 3)O ₂ supply orifice w/air seal 4)O ₂ supply system
Sterilization		To sterilize wastes within incinerator	Raise temperature of wastes to kill all micro-organisms	Electrical heaters	Heated exhaust tube to catalytic afterburner	Possible nonsterilization of isolated waste particles at inlet end	1)Sufficient cooling gas flow through orifice ring to keep orifice clean 2)Prevent build-up of wastes at feed tube (see WASTE FEED ACCOMMODATION above)
Ash Removal		To remove accumulated final ash from incinerator	Backflush with air in through exhaust and out through ash removal tube	Ash removal orifice	Secondary blower loop and filter	Ash residue not completely entrained in reverse air flow	"Fingers" on paddle blades to create mixing for entrainment of all ash particles in backflush

2.4 Catalytic Afterburner

The purpose of the catalytic afterburner or oxidation unit is to accept effluent gases and vapors from the incinerator and to convert any unoxidized materials to an oxidized state for safe discharge. The main requirements of this unit are that it operate continuously, that it accommodate the anticipated gas flow rates without creating large pressure drops, and that it provide complete sterilization of low-temperature volatiles and water vapor.

No preliminary evaluation of this unit was performed since it had been thoroughly evaluated during the previous program (NASA Contract No. NAS 2-5442, GARD Project 1493).

Section 3

TEST RESULTS

In this section, results from laboratory testing of the four major components are presented. In some cases, the tests were performed on simple test set-ups for the purpose of determining concept feasibility only; other tests were more elaborate including five full incineration tests with actual waste materials.

A one-man capacity, stainless steel incinerator, used for initial laboratory testing during the previous program (NASA Contract No. NAS 2-5442, GARD Project 1493), was modified, as needed, and used for all full incineration tests. A plastic model of the rotating-paddle incinerator -- shown in Figure 1 -- was used for many of the other laboratory tests.

3.1 Particle Size Reduction Mechanism

Three particle size reducing mechanisms were tested using simulated human wastes (made from dog food and peanut butter) and toilet tissue. The concepts tested were two versions of the rotating wire slicer and the rotating-paddle blade cutter arrangement.

3.1.1 Rotating Wire Slicer

The first version of the rotating wire slicer was referred to as the "rotating wire loop". It was fabricated using 0.13-cm (0.05-in) diameter steel wire and was mounted within a clear plastic waste transport tube having a 5.1-cm (2-in) ID. The wire loop was rotated within the tube normal to the tube's axis by a direct-drive motor. The motor's drive shaft penetrated the wall of the tube; however, no attempt was made to seal this penetration. A sketch of this concept is shown in Figure 2.

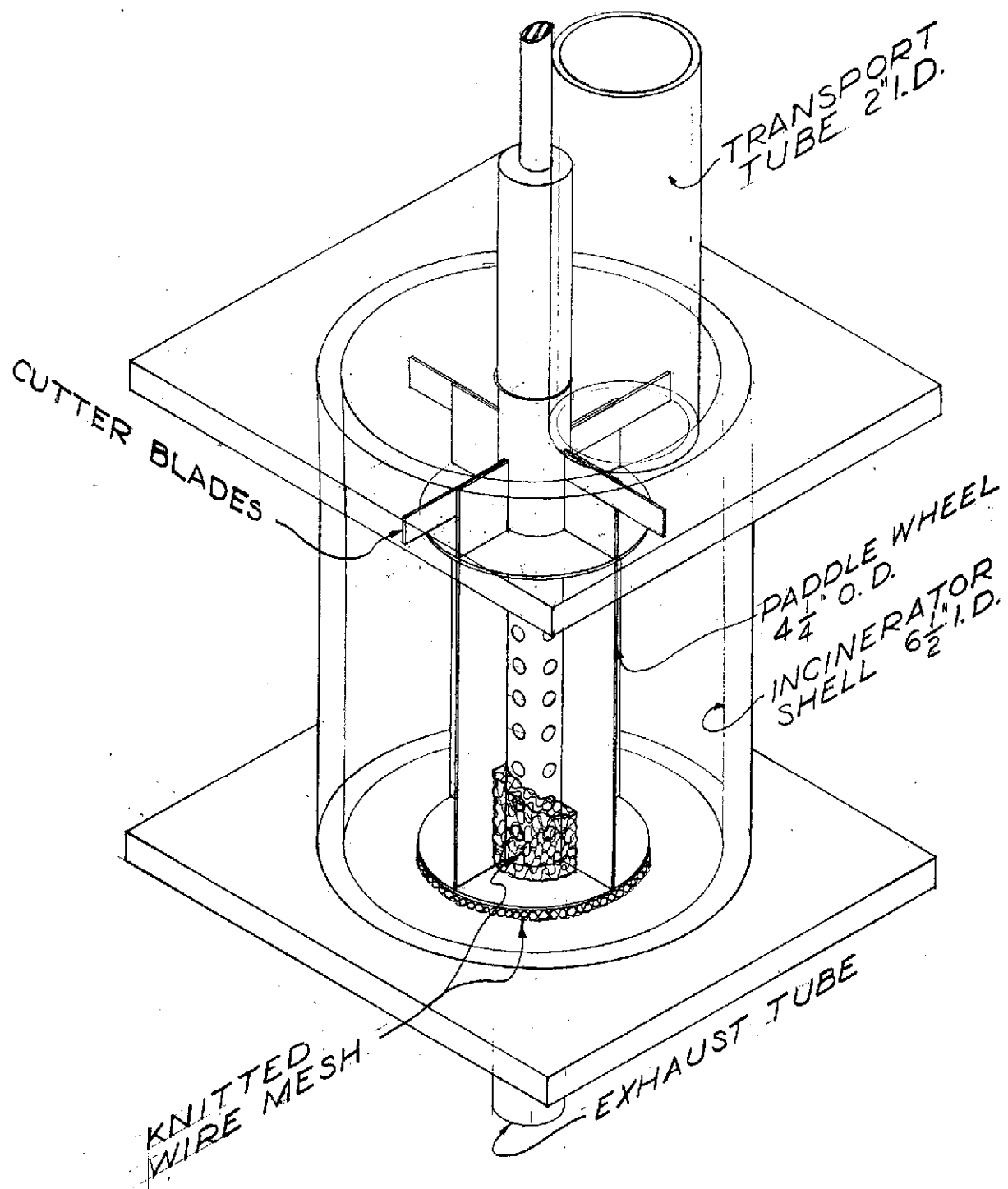


Figure 1. PLASTIC MODEL INCINERATOR

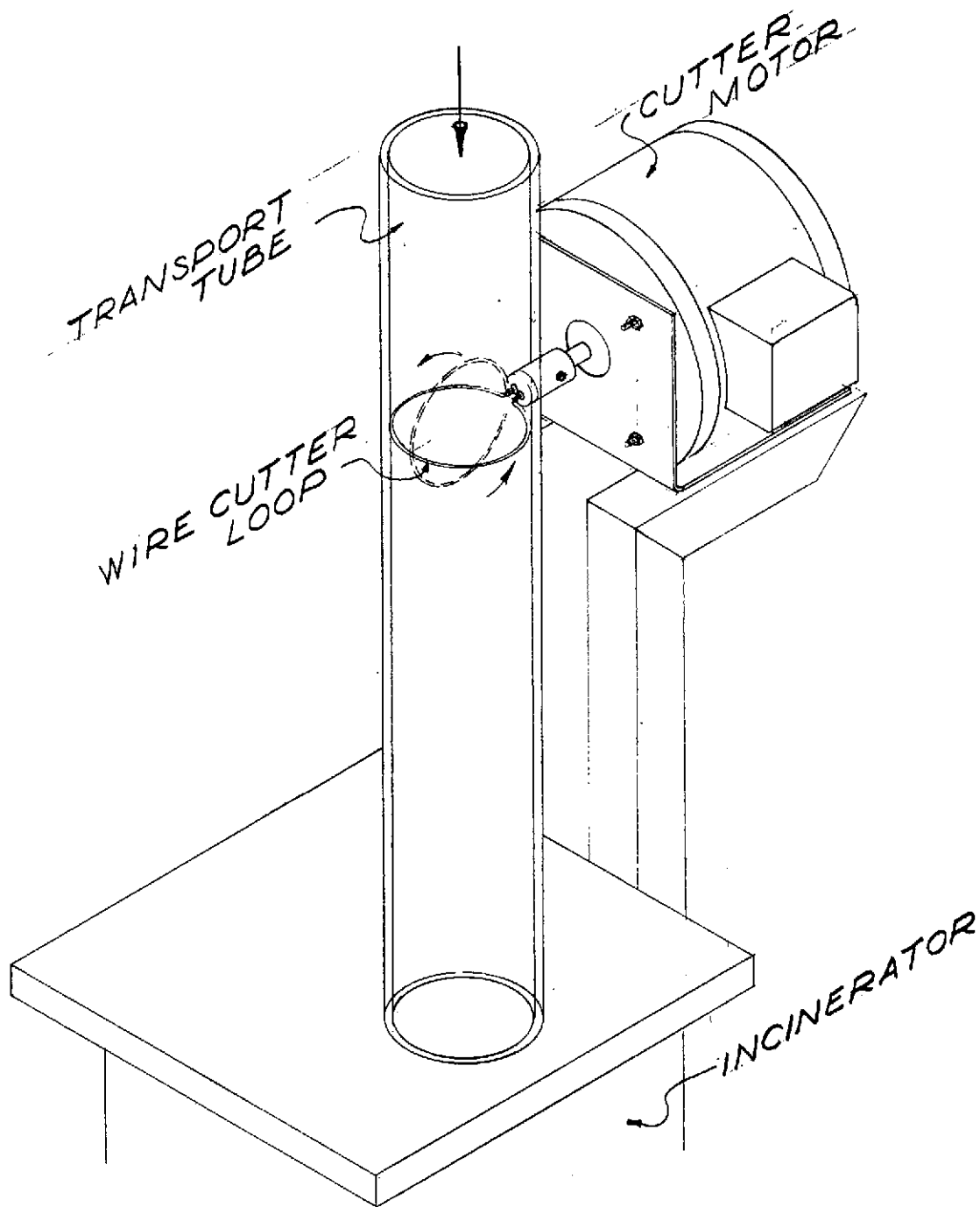


Figure 2. ROTATING WIRE LOOP PARTICLE SIZE REDUCTION MECHANISM

With a rotational speed of 1700 rpm and a shop vacuum cleaner connected to the bottom end of the plastic tube to provide pneumatic drag, both dry and wet wastes were admitted to the top of the tube. Wet and dry toilet tissue either passed through the device largely unaffected or jammed it altogether. Simulated human wastes (dog food and peanut butter) were splattered against the tube walls in the general vicinity of the device. As a result, this concept was eliminated as a viable candidate.

The second version of the wire slicer was referred to as the "rotating wire blade" and was initially fabricated using 0.13-cm (0.05-in) diameter steel wire for both the rotating and fixed wires. In this device, a stationary wire was positioned along the diameter of the transport tube and a second wire blade was made to rotate on top of it in the radial position. A sketch of this concept is shown in Figure 3.

Test results obtained with this arrangement operating at rotational speeds of from 1000 to 5000 rpm using a friction-type drive assembly were much the same as those obtained with the rotating wire loop version, although no waste material passed through the device unaffected.

The two wires were then replaced with steel blades of trapezoidal cross-section for strength [height: 0.18 cm (0.07 in); cutting edge width: 0.32 cm (0.125 in); width of opposite base: 0.10 cm (0.04 in)]. An arrangement to provide a positive drive for the ring holding the rotating wire blade was also designed and fabricated.

At a rotational speed of 5000 rpm, dry toilet tissue was thoroughly shredded by the device while wet toilet tissue tended to be flung out and to collect on the tube walls; simulated human wastes were handled in much the same fashion as the wet toilet tissue. Because of these results, this concept was also eliminated as a candidate.

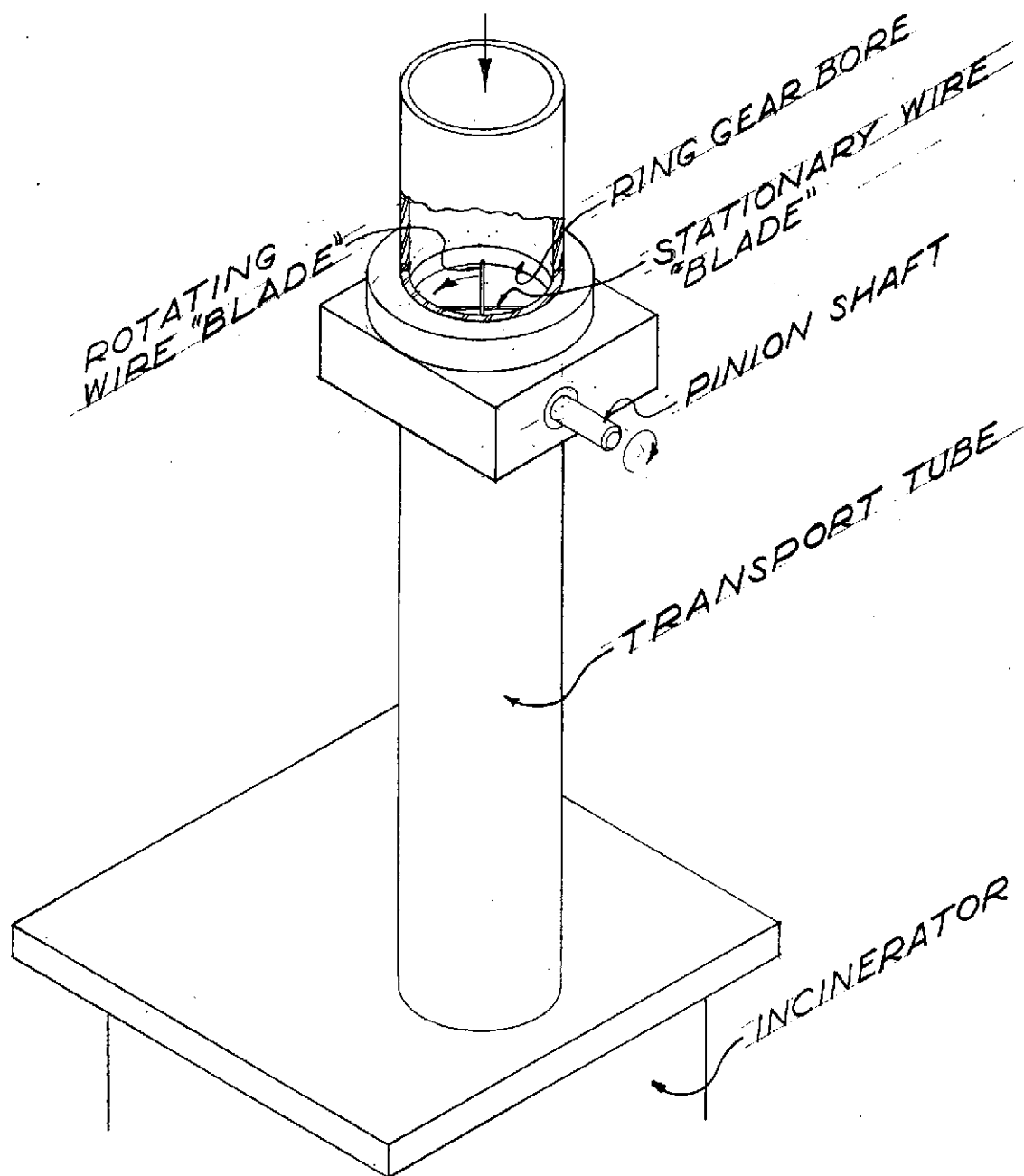


Figure 3. ROTATING WIRE BLADE PARTICLE SIZE REDUCTION MECHANISM.

3.1.2 Rotating-Paddle Blade Cutter

Initial testing of the rotating-paddle blade cutter concept involved the use of 0.16-cm (1/16-in) thick, 1.27-cm (1/2-in) wide "fingers" or cutter blades on each of the four rotating paddle blades at the inlet end of the plastic model incinerator. The purpose of these cutter blades was to slice the waste materials at the transport tube inlet just as the wastes entered the incinerator; this arrangement is shown in Figure 1.

With the paddle blades rotating at 400 rpm and a shop vacuum cleaner connected to the incinerator exhaust tube to create a pneumatic drag, some lodging of dry toilet tissue took place within the clearance gap between the cutter blades and the incinerator end plate; rinse water was partially effective in removing the lodged paper. Simulated human wastes, however, passed easily into the incinerator without lodging.

This configuration was then modified to improve overall performance of the cutters. First, "fingers" were added to the four paddle blades along their length to help distribute the incoming wastes within the incinerator. Second, the clearance gap between the paddle blade assembly and the inlet end of the incinerator was reduced in an attempt to minimize or completely eliminate toilet tissue build-up.

Testing with toilet tissue and simulated human wastes under the same conditions as before resulted in the following observations:

1. The addition of a full set of "fingers" on each paddle blade greatly enhanced the break-up and accommodation of solid and liquid wastes within the incinerator.
2. The reduction of the clearance gap between the paddle blades and the transport tube outlet to essentially "zero" did not significantly reduce the problem of toilet tissue accumulation in this region.

3. Toilet tissue tended to lodge on some of the "fingers" that had been added to the paddle blades.

Figure 4 shows two photographs of this toilet tissue problem.

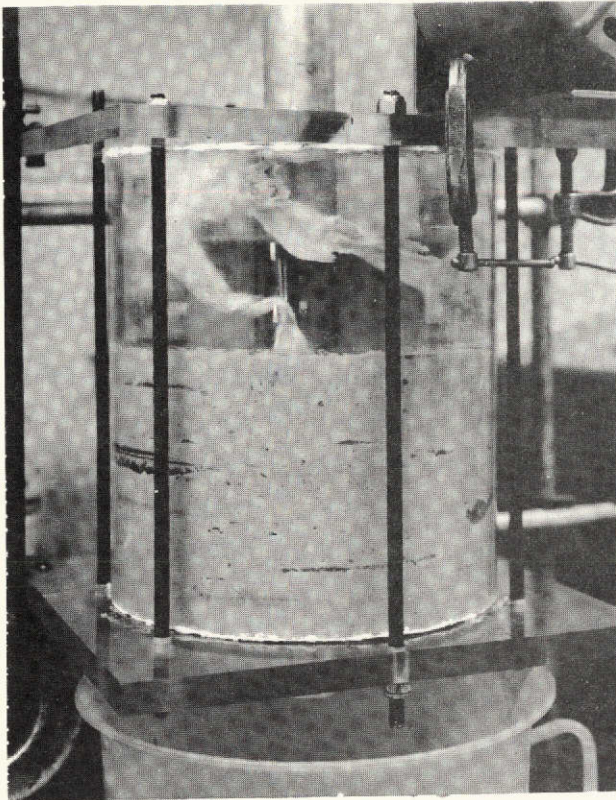
A second modification to this arrangement involved extending the waste transport tube slightly into the incinerator such that it contacted the top edge of each cutter blade (the end of the transport tube was cut to provide a slight ramp to allow gradual contact with each blade as the paddle blade assembly rotated). It was anticipated that toilet tissue would be sheared with this configuration, but complete cutting could not be obtained.

Another modification resulted in the inclusion of a shear bar mounted across the incinerator end plate on a chord passing between the opening for the paddle blade assembly drive shaft and the waste transport tube entrance to the incinerator. The shear bar was sharpened and made to provide continuous contact with the paddle blades. This configuration is shown in Figure 5.

With the paddle blade assembly rotating at 300 rpm and pneumatic drag created as before, both wet and dry toilet tissue were readily sheared and accommodated within the incinerator; candidate disposable liner materials and simulated human wastes were also easily accommodated.

Although this configuration was satisfactory for particle size reduction, the continuous metal-to-metal contact of the shear bar and rotating paddle blades was less than desirable; continuous contact would be difficult, at best, to maintain during extended missions in a fully operational system. For this reason, tests were conducted with a small clearance gap between the paddle blades and the shear bar; a clearance of 0.0025 cm (0.001 in) was selected.

Tests results with this clearance gap were very unfavorable; build-up of toilet tissue at the top of the paddle blade assembly led to eventual jamming of the assembly and stoppage of rotation. Because of this, it was concluded



Photograph from test with model plastic incinerator illustrating characteristic accommodation of water, simulated boli and toilet paper.

Similar photograph. Note in both photographs the accumulation of toilet paper at the top of the paddle blade assembly and on the paddle blade finger extensions.

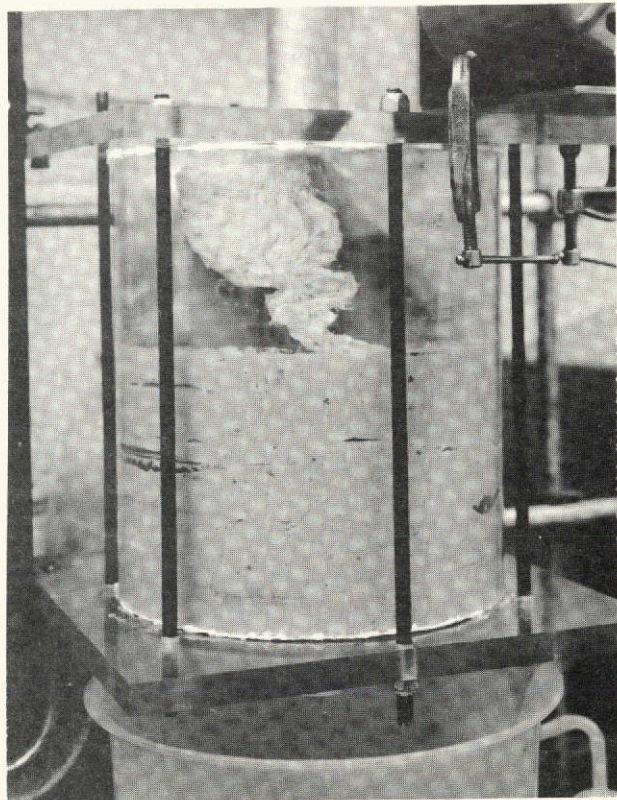


Figure 4. ROTATING-PADDLE BLADE CUTTER TEST RESULTS

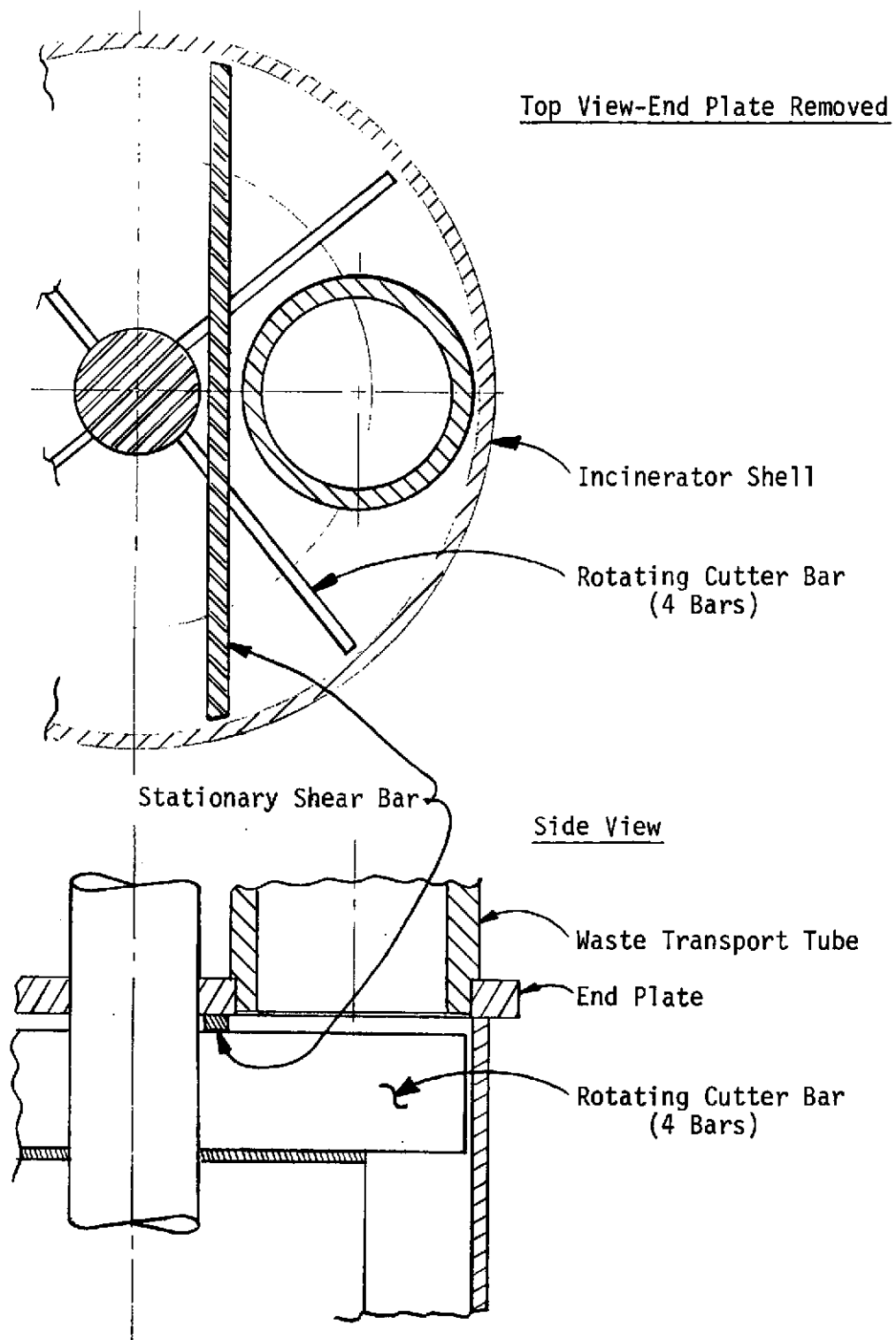


Figure 5. SHEAR BAR PARTICLE SIZE REDUCTION MECHANISM

that successful long-term operation can only be achieved by indexing the paddle blade assembly axially such that metal-to-metal contact between the shear bar and rotating paddle blades can be maintained during loading of the incinerator with wastes and then be removed during all other incinerator operations.

3.1.3 Additional Investigations

Although satisfactory operation of the shear bar/rotating-paddle blade cutter arrangement had been demonstrated, it was still desired to eliminate any metal-to-metal contact. For this reason, a third concept was conceived, fabricated, and tested.

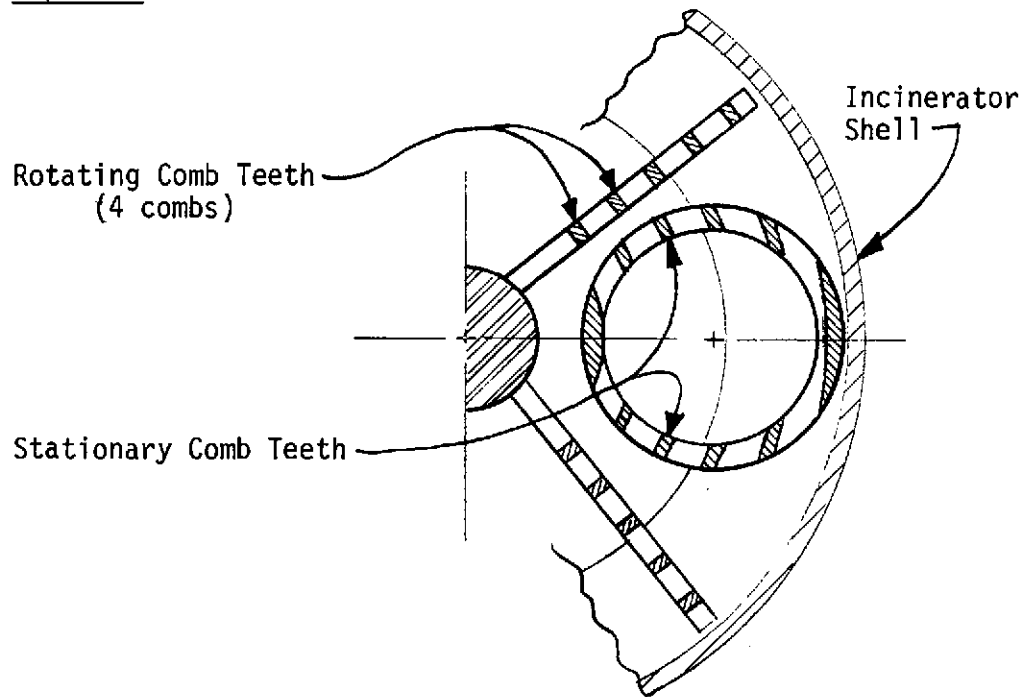
In this new concept, the waste transport tube was extended 1.9 cm (3/4 in) into the plastic model incinerator. This extended portion was cut at different radii to provide a series of 0.32-cm (1/8-in) wide slots such that the remaining metal "teeth" were also 0.32 cm (1/8 in) wide; this configuration resembled a comb. Corresponding "teeth" were added to the top of each paddle blade and arranged such that they passed or "combed" through the transport tube slots. This concept is shown in Figure 6.

Tests with these comb "teeth" blunt, as well as with their leading edges sharpened, proved unsatisfactory. Build-up of toilet tissue on both the stationary and rotating comb "teeth" consistently led to jamming of the mechanism and stoppage of rotation. No additional investigation on this or any other particle size reduction mechanism was performed.

3.2 Pneumatic Waste Transport System

All of the suggested concepts for the waste transport system utilized a blower, located downstream of the system, to create pneumatic drag on the collected waste particles to move them from the collection site (commode) to the rotating-paddle incinerator (see Table VI). The suggested concepts varied

Top View



Side View

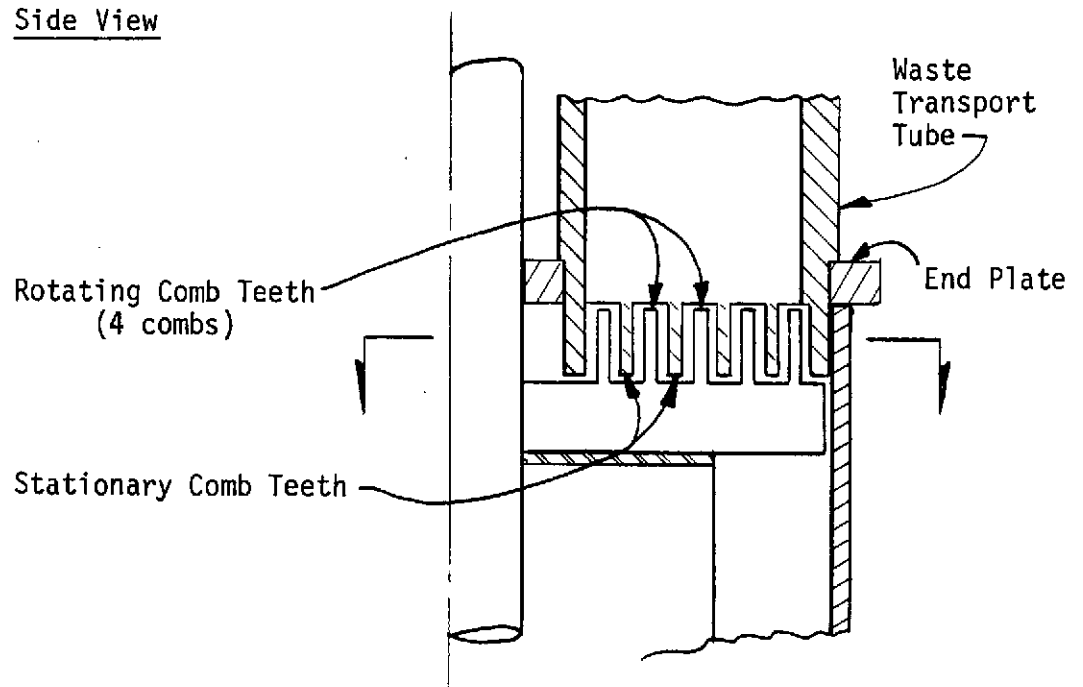


Figure 6. COMB PARTICLE SIZE REDUCTION MECHANISM

only in their method of keeping the inside walls of the transport tube clean; these methods were therefore the primary subject for evaluation.

Three candidate concepts for the pneumatic waste transport system were evaluated in this sense in the laboratory; these were: "blower and ultrasonic tube", "blower and water-rinsed porous wall tube", and "blower and liner".

3.2.1 Blower and Ultrasonic Tube

In this concept, wastes are pneumatically transported through an unlined tube. Following waste loading and a water rinse to dislodge large stray waste particles, ultrasound is employed to vibrate the tube walls and dislodge all stray particles. Pneumatic air drag then carries the freed particles into the incinerator.

A laboratory ultrasonic cleaning tank was used as the test bed. In all cases, a simulated waste mass (dog food and peanut butter), placed on the inside of a metal tube could not be broken free by the ultrasound. The tube was tested both in free air and immersed in water, which provided a more suitable medium for carrying the sound waves from the ultrasonic generator to the tube being tested. Because of the unsuccessful performance of this technique, it was eliminated as a viable candidate.

3.2.2 Blower and Water-Rinsed Porous Tube

In this concept, wastes are pneumatically transported through a tube having porous walls. An outer tube, placed and sealed around the porous tube, is filled and continually supplied with water under a slight pressure. This pressure forces the water to flow through the pores of the tube wall and "bleed" on the inside of the tube providing a constant, thin film of water to prevent adhesion of waste particles.

To evaluate this concept, a thin, porous, stainless steel flat plate having 0.5-micron pores (the smallest pore size available) was sealed over a cylindrical chamber into which tap water was admitted from a laboratory sink.

The results of this test were basically that water flowed through the pores freely but unevenly with a drop of only a few millimeters of water pressure across the plate. Because proper control of the water flow through this material appeared to be extremely difficult, this concept was also eliminated as a viable candidate.

3.2.3 Blower and Liner

This concept employs a disposable liner to keep the inner walls of the transport tube clean. Wastes are pneumatically transported through the tube and are allowed to contact the liner, which is then released and pneumatically transported into the incinerator and processed along with the wastes. A sketch of this concept is presented in Figure 7.

Inquiries were sent to several paper liner manufacturers across the country to obtain samples of candidate materials for use as a disposable liner. As a basis for their selection of candidate materials, the companies were asked to send samples that could be characterized as follows:

- Nonabsorbent (waterproof or water-repellent)
- Easily torn
- Combustible with no offensive off-gases
- Flexible
- Less than 0.025 cm (10 mils) thick
- Resistant to oil and grease

Nineteen samples were received and tested. The samples were tested with respect to their ability to repel over a period of one hour: tap water, a dilute solution of "Aqua Kem" (a formaldehyde disinfectant made by Thetford

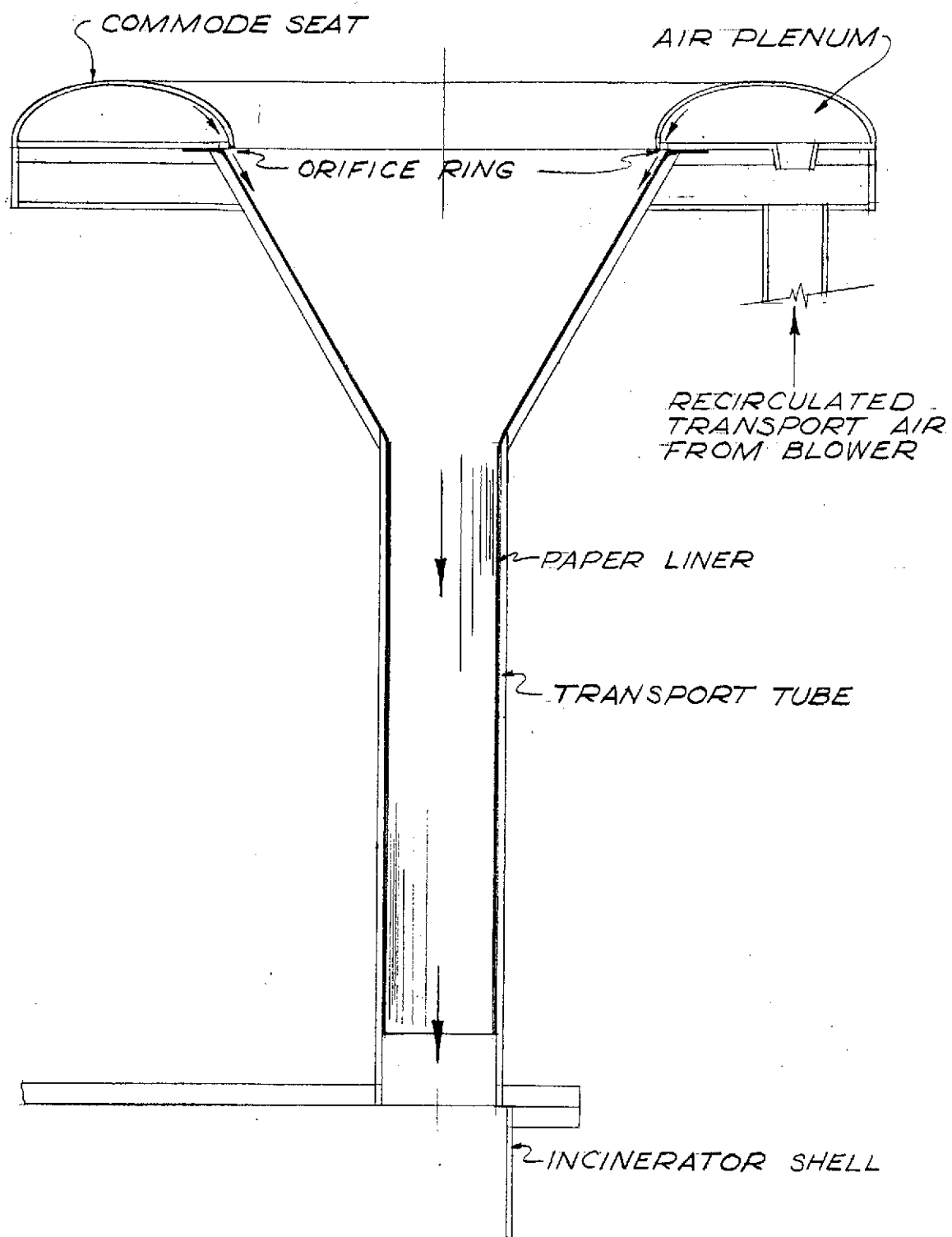


Figure 7. TRANSPORT TUBE DISPOSABLE LINER
(Liner Incinerated after One or
More Defecations)

Engineering Corporation), and urine distillate residue (50% solids). The nineteen samples are presented in Table VIII along with the results of the absorbency tests.

As noted in this table, eleven samples were found to be satisfactory, and of these eleven, five passed all tests; these five are double-checked in the last column of the table. (The other six were borderline cases.) Although the "window shade" sample passed all tests, it was quite thick and difficult to tear; for this reason, it was eliminated as a candidate. The remaining ten satisfactory samples all appeared to tear easily and remain viable candidates. (No thickness or tear strength measurements were performed; final selection of a disposable liner material will be based upon the results of preliminary integrated subsystem testing later in the program.)

3.3 Rotating-Paddle Incinerator

3.3.1 Actual Dry Incineration Tests

The test set-up used for evaluating the rotating-paddle incinerator consisted of a 14-cm (5-1/2-in) diameter, 15.2-cm (6-in) long, stainless steel stationary shell fitted on one end with a removable, flanged cover plate. This cover plate was fitted with a pneumatic waste transport tube and a sealed bearing housing; this housing contained a drive shaft with support bearings. The drive shaft was connected on one end to a rotating paddle blade assembly located inside the stationary shell and on the other end to a variable-speed motor. Air was admitted initially to the bearing housing to cool the bearings and to provide a positive seal between the rotating drive shaft and the removable, flanged cover plate (no dynamic mechanical seal was employed due to its low reliability in this application).

Table VIII CANDIDATE DISPOSABLE LINER MATERIALS

MANUFACTURER	PAPER-LINER DESIGNATION	ABSORBENCY TEST ^δ			SUCESSFUL CANDIDATES
		TAP WATER	AQUA-KEM*	UDR**	
JOANNA WESTERN MILLS CHICAGO, ILLINOIS	"WINDOW SHADE"	+	+	+	✓✓
CENTRAL STATES PAPER CO. ST. LOUIS, MISSOURI	(a) 48# DRY WAX (b) 48# PTM	+	(b)	+	✓
		+	(b)	+	✓
THILMANY PAPER DIVISION KOCHANA, WISCONSIN	(a) 17.5# WHITE #84600 M.G. KRAFT- 3.5# POLY	+	-	+	
	(b) 20# WHITE #84600 M.G. KRAFT-5# POLY	+	-	+	
	(c) 20# NAT'L #53600 M.G. KRAFT-10# POLY	+	+	+	✓✓
	(d) 20# WHITE #83600 M.G. KRAFT-4# WAXSORB	+	+	+	✓✓
	(e) 25# NAT'L #53600 T/W-SIZED M.G.	-	-	-	
	(f) 25# WHITE #84600 T/W-SIZED TL-30 MED.	-	-	-	
EDGEWATER PAPER COMPANY MENASHA, WISCONSIN	(a) LABEL 60# WAXED CREPED KRAFT- 33-1/3% STRETCH	+	-	+	
	(b) 30-15 UBL 20-2	+	-	-	
H.P. SMITH PAPER COMPANY CHICAGO, ILLINOIS	(a) LOXOL 40# BLEACH- ED KRAFT-COATED	+	+	+	✓✓
	(b) 30# BLEACHED KRAFT-COATED WITH 1/2 MIL POLY	+	(b)	+	✓
	(c) 20 BELOW - 35# BLEACHED KRAFT- COATED WITH 5# POLY	+	(b)	+	✓
	(d) FLYOL WRAP 100	+	(b)	+	✓
GLAS-KRAFT, INC. SLATERSVILLE, RHODE ISLAND	GLAS-KRAFT	-	-	-	
INDUSTRIAL PKG. PRODS. CO. RIVERTON, NEW JERSEY	40# NAT'L KRAFT- 48# DRY WAX	+	+	+	✓✓
HERSEY PAPER LINING CO. MELROSE, MASSACHUSETTS	30/15/30	+	-	-	
SCOTT PAPER COMPANY PHILADELPHIA, PENNA.	"CUT-RITE" WAXED PAPER	+	(b)	+	✓

* THETFORD ENGINEERING CORP. - DILUTED WITH WATER

** URINE DISTILLATE RESIDUE - 50% SOLIDS

^δ +: PASSED (DID NOT ABSORB SOLUTION)

-: FAILED (SOLUTION BLED THROUGH TO WET PAPER BLOTTER UNDERNEATH)

(b): BORDERLINE (SOLUTION BLED THROUGH BUT DID NOT WET PAPER BLOTTER)

The opposite end of the stationary shell contained a closed end plate fitted in the center with a fixed exhaust tube. The drive shaft extended the full length of the incinerator shell along its axis and contained four paddle blades located 90° apart. Within the incinerator, the drive shaft -- or central rotating tube -- contained a large number of holes between each paddle blade; these holes allowed for the removal of transport and generated gases to the fixed exhaust tube. Inconel wire mesh was initially placed over the holes as well as in the space between the rotating paddle blades and the fixed, closed end plate of the incinerator. This configuration is sketched in Figure 8 (the dimensions in this figure are expressed in inches).

The central tube and paddle blades were continuously rotated at a fixed speed to impart a centrifugal force to the waste materials to confine them within the annular space between the blades and the stationary shell. The Inconel wire mesh was used to prevent stray liquid droplets and solid waste particles from entering the exhaust tube. Cylindrical, electrical resistance heaters and suitable insulation were positioned around the outside of the stationary shell.

A series of five full incineration tests were run with this arrangement, all with the incinerator positioned horizontally. Modifications were made, as needed, before each test.

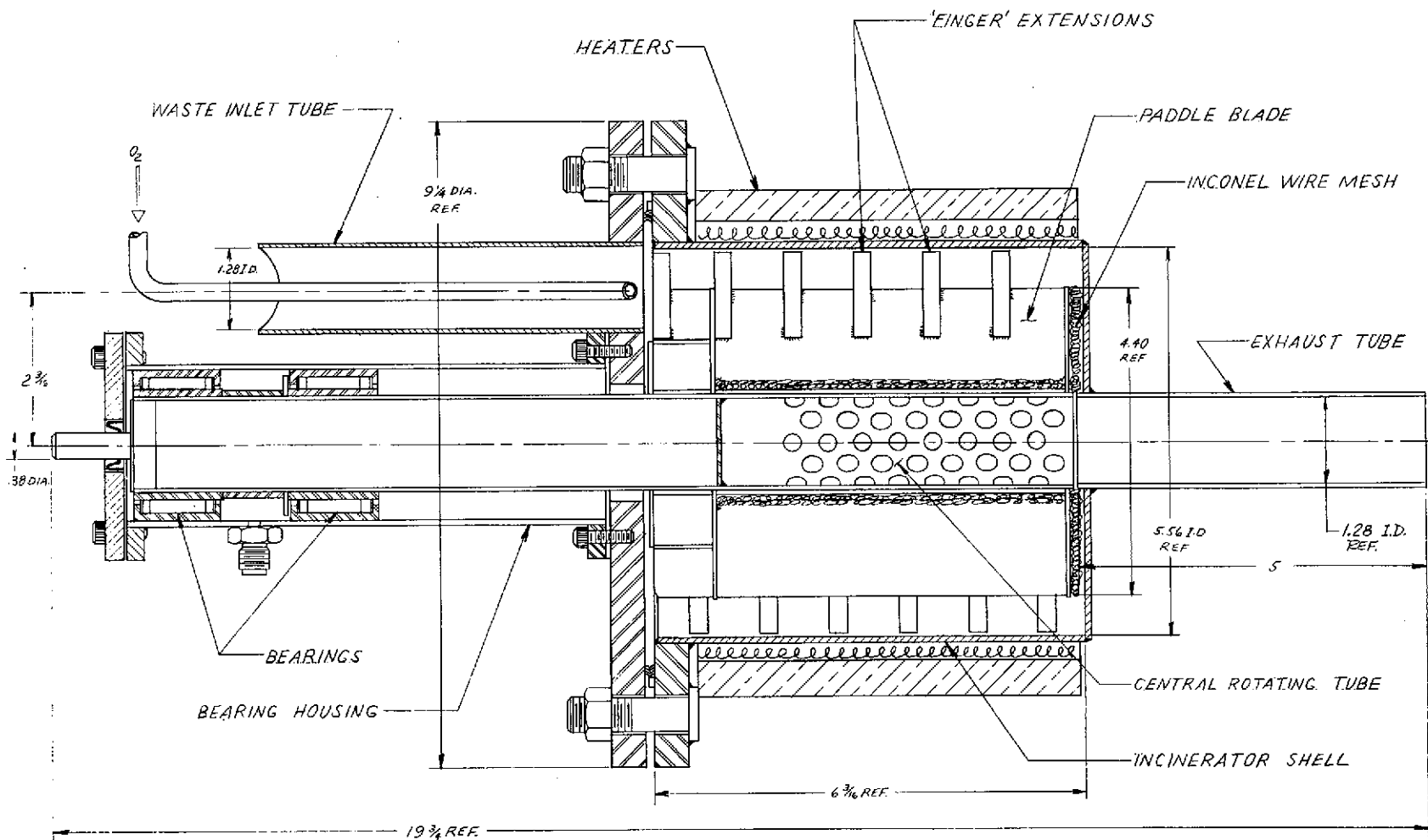


Figure 8. ROTATING-PADDLE INCINERATOR -
LABORATORY TEST SET-UP

The waste loads for these tests are described below:

<u>Tests 1-4</u>		<u>Test 5</u>
400 grams	Feces	300 grams
400 grams	Urine distillate residue	300 grams
10 grams	Toilet tissue	10 grams
<u>130 grams</u>	Water	<u>100 grams</u>
940 grams	TOTAL	710 grams

A lower sample weight was used in Test 5 due to the higher solids concentration of the urine distillate residue (65.4% solids in Test 5 as opposed to 45.6% solids in Tests 1-4).

All incineration tests were performed employing the normal dry incineration process; that is, wastes were admitted to the incinerator at room temperature and continuously heated to approximately 540°C (1000°F). At this temperature, the heaters were shut off and oxygen was admitted for final combustion. The typical dry incineration cycle consists of three phases:

1. Boil-off of low-temperature volatiles and water from ambient temperature to 100°C (212°F),
2. Pyrolysis (thermal decomposition in the absence of oxygen) of the dehydrated wastes from 100°C (212°F) to 540°C (1000°F), and
3. Final combustion with oxygen of the pyrolysis residue at 540°C (1000°F) to 650°C (1200°F).

Oxidation of the evolved gases and vapors in a catalytic afterburner was not performed.

The results and observations from each of the five incineration tests are described on the following pages.

Test 1 - For the first test, the incinerator was manually loaded with the waste load noted above. The paddle blade assembly was run at a rotational speed of 140 rpm throughout the incineration cycle until completion of the combustion process. Similarly, an air flow of approximately 100 ml per minute was maintained through the bearing housing into the incinerator. At an incinerator temperature of approximately 500°C (940°F), the heaters were turned off, and oxygen was bled into the incinerator at a rate of approximately 1 liter per minute through a perforated stainless steel tube [0.64-cm (1/4-in) diameter] mounted within the paddle blade assembly support shaft (which also served as the exhaust tube for gases emanating from the incinerator). After 28.3 liters (1 standard cubic foot) of oxygen had been supplied, the entire system was shut down.

Inspection of the incinerator after cool-down yielded the following observations. Upon opening the incinerator, there was a strong odor of ammonia. Also, a large amount of residue had accumulated near the inlet end of the incinerator at the bottom and was rather firmly caked on the incinerator walls. It did not appear to be as completely incinerated as the ash found elsewhere within the incinerator. A layer of ash had also formed on the knitted Inconel wire mesh fastened to the paddle blade assembly support shaft. This ash was brittle and, at most, 0.16 cm (1/16 in) thick. The color of the ash throughout the incinerator was generally coal black. (The ash within the incinerator was collected as completely as possible and found to have a mass of 90 grams.)

As a result of this first incineration test, it was decided to modify the paddle blade assembly to provide mechanical removal of ash along the walls of the incinerator. "Fingers" of 0.08-cm (0.031-in) thick Hastelloy-X were welded to the paddle blades. These "fingers" can be seen in Figure 8.

The radial position of these fingers was such that a clearance gap of 0.13 cm (0.05 in) existed between the outside edge of the fingers and the inside wall of the incinerator shell. It was also decided to increase the rotational speed of the paddle blade assembly for the second incineration test to 220 rpm to reduce the possibility of ash build-up on the wire mesh. To prevent ash build-up and caking within the incinerator during cool-down after the incineration process, it was decided to maintain the rotation of the paddle blade assembly during this cool-down period.

Test 2 - The second incineration test was run with the same waste load as the first. Air and oxygen introduction into the incinerator were also performed in a fashion similar to that of the first test.

During the process of pyrolysis, at an incinerator temperature of about 480°C (900°F), large quantities of white smoke billowed from the incinerator for approximately 15 minutes. This was followed by an explosion-like phenomenon which took place at a temperature of 540°C (1000°F), again during the process of pyrolysis (no damage was done to the incinerator). The electrical heaters were shut off at a temperature of 565°C (1050°F), and oxygen was introduced with the incinerator at this temperature [approximately 40°C (100°F) higher than for the first test].

Inspection of the incinerator after cool-down yielded these observations. The ash in the incinerator was generally coal black and consisted of much finer particles than that of the first test. The walls of the incinerator exhibited no ash adherence. The wire mesh fastened to the paddle blade assembly was partially covered (over about 20% of its area) with ash. This build-up was primarily in the region where the wire mesh contacted each paddle blade, on those sides facing in the rotational direction. Some ash residue was also found in the exhaust tube; its color was light brown or rust, the color expected

for completely oxidized waste products. (The ash was collected as completely as possible and found to have a mass of 74 grams.)

From this test it was concluded that: (1) the fingers had provided satisfactory removal of ash from the incinerator walls, (2) the higher rotational speed used for the paddle blade assembly had reduced, but not eliminated, the problem of ash build-up on the wire mesh, (3) the ash build-up within the exhaust tube indicated that some leakage of wastes had taken place, (4) the variation in ash color at various locations within the incinerator indicated that most of the oxygen supplied during the final combustion phase did not enter the annular region of the incinerator but simply short-circuited out the exhaust tube, and (5) careful attention is required to determine if the observed smoke generation and subsequent "explosion" were anomolous or typical of the dry incineration process.

To verify the fourth observation, the ash from this incineration test was run through another incineration cycle, with the oxygen supply tube inserted (as shown in Figure 8) through the inlet tube to insure adequate oxygen circulation within the annular region of the incinerator. Oxygen introduction into the incinerator for this test was performed at an incinerator temperature of 690°C (1280°F).

As expected, the ash remaining after this "reheat" test exhibited the light brown/rust color characteristic of fully oxidized human waste products. Some adherence of this ash was noted in the form of small clumps loosely adhering to the paddle blades. The rest of the ash also exhibited this tendency to agglomerate somewhat.

Another result of this test was the significant wearing of the Inconel wire mesh used to obtain a partial seal between the paddle blade assembly end plate and the end plate of the incinerator at the fixed exhaust tube.

This seal quite obviously required significant improvement prior to long term incinerator operation.

On the basis of these test results, it was decided that an incineration cycle must be run with oxygen supplied through the inlet tube in order to verify satisfactory operational performance of the rotating-paddle incinerator with respect to ash adhesion and build-up problems, and with respect to oxidation of the wastes and the nature of the resultant ash. It was also concluded that the knitted Inconel wire mesh fastened to the paddle blade assembly (with the exception of that used for an end seal) should be removed to determine the extent of ash build-up that would occur within the paddle blade assembly and exhaust tube in the absence of this mesh.

Test 3 - The third incineration test was run with the same waste load and air introduction into the incinerator through the bearing housing as the previous two tests.

The paddle blade assembly was run, with two unfortunate exceptions, at a rotational speed of 300 rpm throughout the incineration cycle and also during cool-down. Once, during loading of the waste materials into the incinerator, the motor for the paddle blade assembly became disengaged from the assembly support shaft. This problem was corrected within one minute. Then, during the pyrolysis phase of the dry incineration cycle, with the incinerator at a temperature of 290°C (550°F), all power to the system was lost due to an apparent overload in the electrical circuit for the incinerator heaters. This problem was corrected only after the incinerator temperature had dropped approximately 50°C (120°F).

As before, the incinerator was heated externally by cylindrical, electrical resistance heaters during the processes of boil-off and pyrolysis, in this case to a temperature of 665°C (1230°F). The heaters were then turned off,

and oxygen was bled at a rate of approximately one liter per minute through a supply tube inserted through the inlet tube to the incinerator. A total of 28.3 liters (1 standard cubic foot) of oxygen was supplied.

Inspection of the incinerator after cool-down yielded the following observations. The ash in the incinerator was generally coal black rather than light brown or rust, the color expected for completely oxidized human waste products. Most of this ash had collected within the paddle blade assembly support shaft and within the incinerator exhaust tube itself. This tube was almost completely blocked with ash. Because of this ash accumulation within the exhaust tube, it appeared that a significant amount of the oxygen supplied to the incinerator simply exited through the incinerator inlet tube without actually coming in contact with the wastes.

The observed pattern of ash accumulation may have been due, all or in part, to the stoppages in the rotation of the paddle blade assembly which took place during this test. As a result, a fourth full incineration test was planned for basically the same reasons that this third test was performed. Also, to insure that proper oxygen distribution would be obtained within the incinerator, the inlet tube was fitted with a plug to force the oxygen to flow through the incinerator and out the exhaust tube. Finally, on the basis of results from the previous program (NASA Contract No. NAS 2-5442, GARD Project 1493), more than 28.3 liters (1 standard cubic foot) of oxygen should have been supplied to the incinerator during the previous incineration tests. As much as 113 liters (4 standard cubic feet) of oxygen may have been required for proper incineration of the waste load used; accordingly, a larger quantity of oxygen was supplied to the incinerator during the fourth incineration test.

Test 4 - Because of the malfunctions described above, a fourth incineration test was performed with the previously suggested modifications. In addition, filtering of the exhaust gases was performed to determine what type of, as well as how much, particulate matter is entrained in these gases.

A 0.96-cm (3/8-in) long stainless steel plug was made for insertion into the top end of the inlet tube immediately after loading of the wastes into the incinerator. The plug was made so that the oxygen supply tube could be inserted through it, and a rubber wrapper was provided for sealing the plug and inlet tube externally. The fixed exhaust tube was extended to accommodate an Inconel knitted wire mesh "prefilter", and a filter housing was added to the exhaust tube to hold a 10.2-cm (4-in) diameter, glass-fiber filter capable of removing particulates with diameters larger than 0.3 micron. [This filter's properties were found to remain unchanged in electric furnace tests at temperatures up to 540°C (1000°F).] A short extension of the fixed exhaust tube was also added beyond this filter, and strip heaters and insulation were wrapped around the whole arrangement to allow for maintenance of the exhaust gas temperature at a level sufficient to prevent condensation. Thermocouples for monitoring temperatures were positioned on the filter housing and at the end of the exhaust tube on the inside.

As during the previous test, the paddle blade assembly was run at a rotational speed of 300 rpm throughout the incineration cycle and also during cool-down. The waste load used was the same as that of the previous incineration tests. Similarly, an air flow of 100 ml per minute was maintained through the bearing housing into the incinerator.

For this test the incinerator was heated during the processes of boil-off and pyrolysis to a temperature of 540°C (1000°F). The heaters were then turned off, and oxygen was bled at the usual rate of one liter per minute

through the supply tube inserted in the inlet tube of the incinerator. A total of approximately 85 liters (3 standard cubic feet) of oxygen was supplied (three times the amount supplied during the previous test). To prevent vapor condensation, the exhaust tube and filter housing were maintained at a temperature of 370°C (700°F) throughout the test and during the initial portion of cool-down.

The following observations were made during the course of the test. First, for three minutes during the latter part of pyrolysis, a large quantity of smoke was observed in the exhaust gas [at an incinerator temperature of 510°C (950°F)]. Second, the incinerator temperature increased steadily during the introduction of oxygen from 540°C to 650°C (1000°F to 1200°F) and then decreased from that point on. Coincident with the incinerator temperature attaining 650°C (1200°F), the filter housing temperature increased rapidly from 370°C (700°F) to slightly above 540°C (1000°F) and then decreased again. All of this happened at the time that 42.4 liters (1.5 standard cubic feet) of oxygen had been supplied to the incinerator.

Disassembly of the incinerator after cool-down led to the following observations, many of which are illustrated in Figures 9-11. The ash contained within the incinerator proper (36.5 grams, see Figure 9) was light brown in color and was of two consistencies, fine powder and grains. Some of this ash was hardened in ridges. These ridges corresponded in location to paddle blade assembly "finger" extensions which had been bent by as much as 90° (nine of the 23 "finger" extensions were significantly bent, two at 90° -- see Figure 10). The initial portion of the fixed exhaust tube (see Figure 9) contained a significant amount of hard brown ash (10.5 grams). The inlet tube also contained similar ash (10 grams). The filter (see Figure 11) contained very fine ash (3 grams) which was both black and brown. [It should be noted that the center

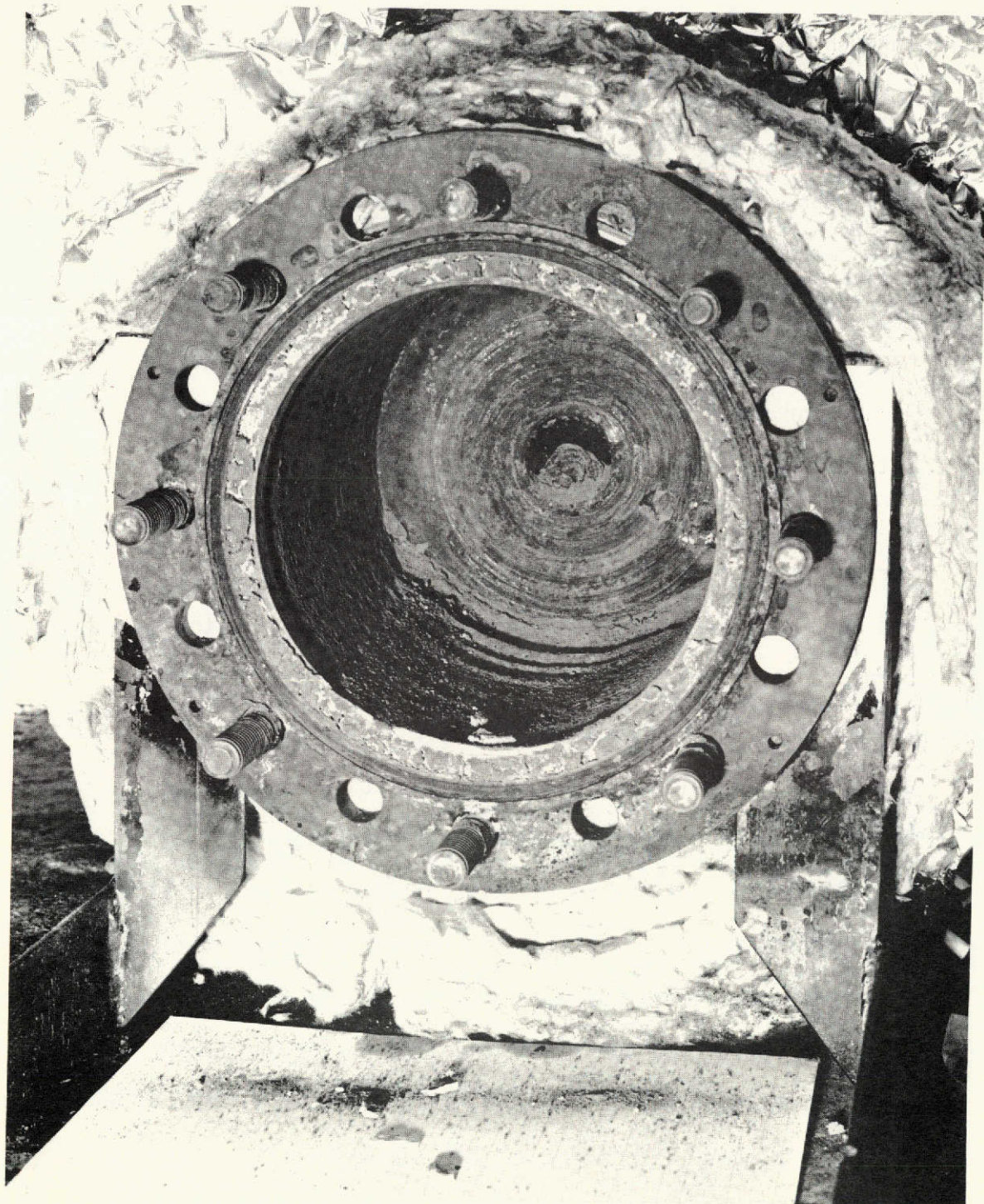


Figure 9. RESULTS OF INCINERATION TEST 4: PHOTOGRAPH OF
INCINERATOR SHELL SHOWING FINAL ASH AND ASH
ACCUMULATION IN EXHAUST TUBE

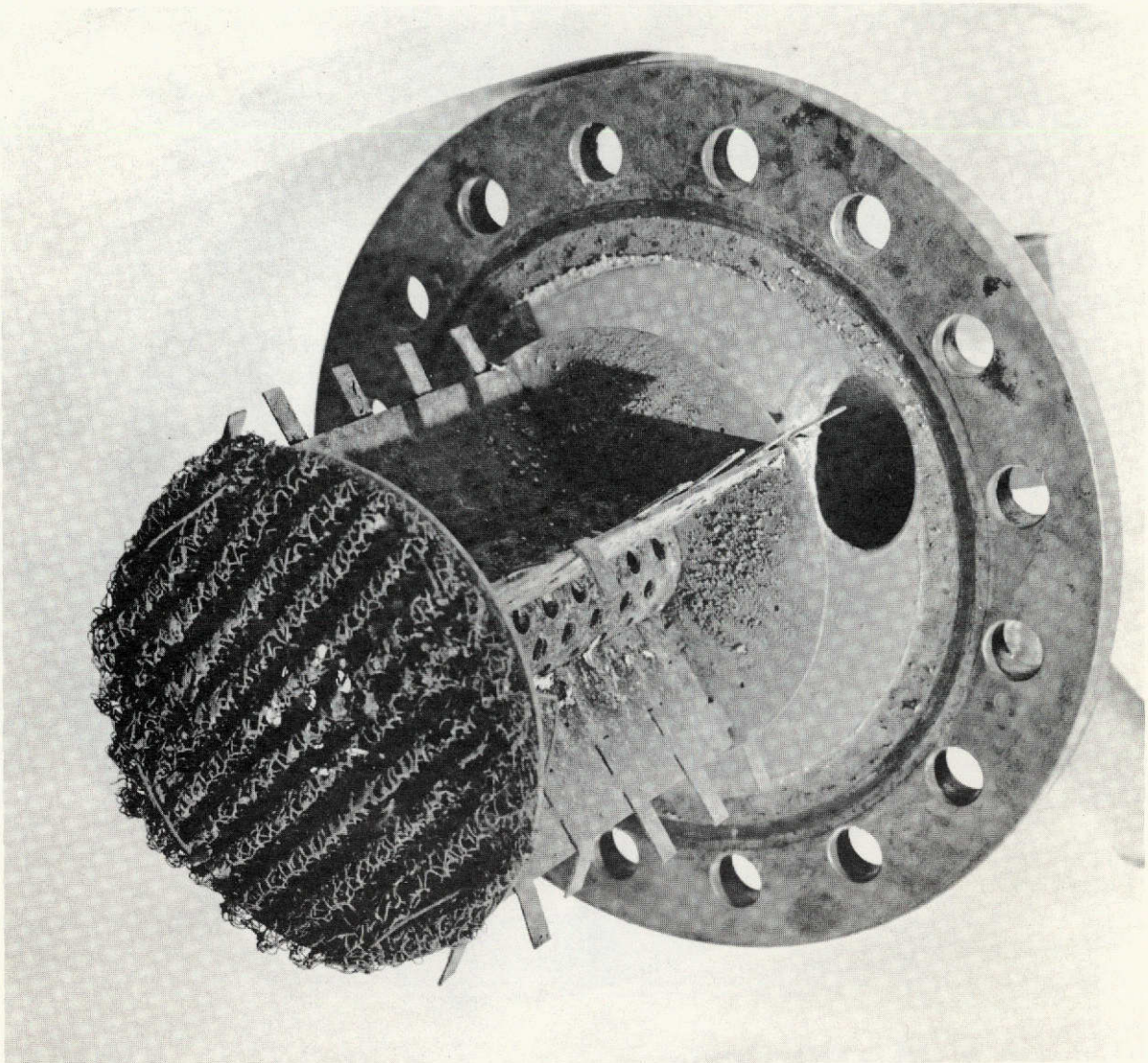


Figure 10. RESULTS OF INCINERATION TEST 4: PHOTOGRAPH OF
PADDLE BLADE ASSEMBLY SHOWING BENT
FINGER EXTENSIONS

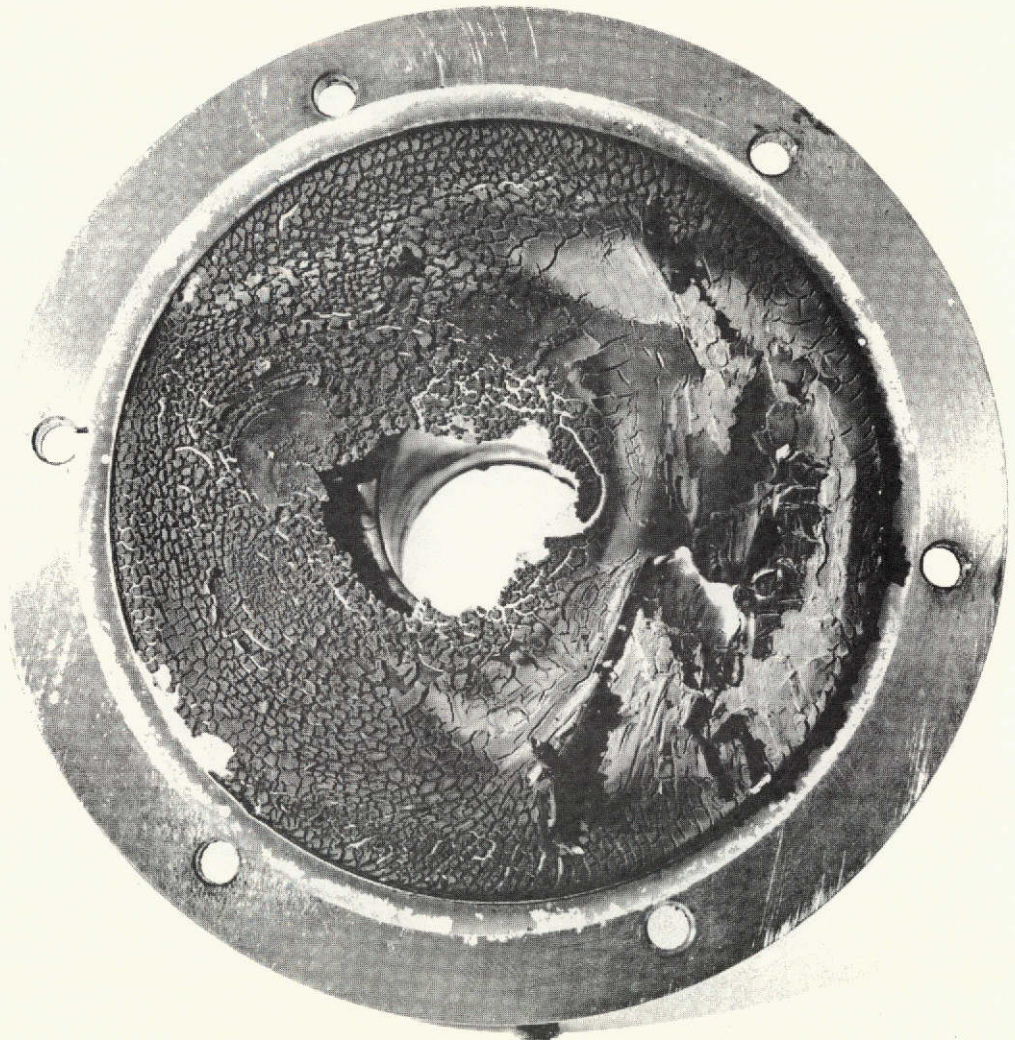


Figure 11. RESULTS OF INCINERATION TEST 4: PHOTOGRAPH OF
INCINERATOR SIDE OF EXHAUST TUBE FILTER
SHOWING BUILD-UP OF FINE PARTICULATES

portion of this filter fell out during either cool-down or disassembly. It undoubtedly became brittle at the end of the oxidation process when temperatures somewhat in excess of 540°C (1000°F) were noted on its surface.] Finally, the bearing housing itself contained throughout its length a significant amount of, at best, partially processed black wastes (approximately 25 grams).

The following conclusions were reached as a result of this test:

1. The smoke-off observed during the latter part of pyrolysis appeared to have resulted from late processing of the wastes trapped at the bottom of the inlet tube (which undoubtedly remained at a lower temperature than the incinerator proper).
2. The amount of oxygen required to oxidize the pyrolysis products contained within the incinerator and the exhaust tube was very nearly 42.4 liters (1.5 standard cubic feet), but this figure is lower than that required to process the full waste load used because of the partially processed wastes found in the bearing housing and the inlet tube.
3. Bending of the paddle blade assembly "finger" extensions appeared to have been a result of hardening of the waste ash and/or reduction of material strength.
4. Much of the ash in the exhaust tube appeared to have collected there as a liquid (through leakage) and then to have been processed.
5. The wastes found in the bearing housing apparently leaked there in liquid form early in the test.
6. Many of the particulates collected on the filter apparently underwent oxidation there (that is, they arrived at the filter prior to the final combustion phase of processing).

To determine what caused the bending of the "finger" extensions, small samples (approximately 70 grams) of the usual waste mixture were run through two incineration cycles in an Inconel 600 metal container over an open burner [maximum sample temperature: 580°C (1070°F)]. The temperature of the wastes was monitored, and the wastes were observed for changes in characteristics. At no point during either pyrolysis or oxidation was any significant amount of hardening observed. The ash remaining after the oxidation process was then placed in an oven and heated to 790°C (1450°F) in an attempt to induce hardening, again without significant effect.

As a result of these tests, further investigation into the properties of the Hastelloy-X "finger" extensions was made. Beam bending calculations for the 1.3-cm (1/2-in) long, 0.08-cm (0.01-in) thick "fingers" showed that, at 650°C (1200°F), a normal force of 133,500 dynes (3 lb) on the free end of such a "finger" would lead to a 0.025-cm (0.01-in) deflection at the free end and plastic deformation on the outer surfaces at the opposite, fixed end. Consequently, it was concluded that permanent bending of the "fingers" may have taken place gradually during the latter stages of the oxidation process, with the ash building up accordingly.

To determine the extent of liquid waste leakage into the exhaust tube and the bearing housing, the incinerator was cleaned after inspection and reassembled for running with water. Significant leakage of water was observed at both locations while running with only 100 cc of water.

Test 5 - Due to the test results and conclusions just discussed, a fifth full incineration test was run with the incinerator modified essentially as shown in Figure 12 (the dimensions shown in this figure are expressed in inches). Modifications included: (1) an inlet tube plug that is flush with the inner surface of the incinerator inlet end plate, (2) a new seal between the paddle blade assembly support shaft and the incinerator

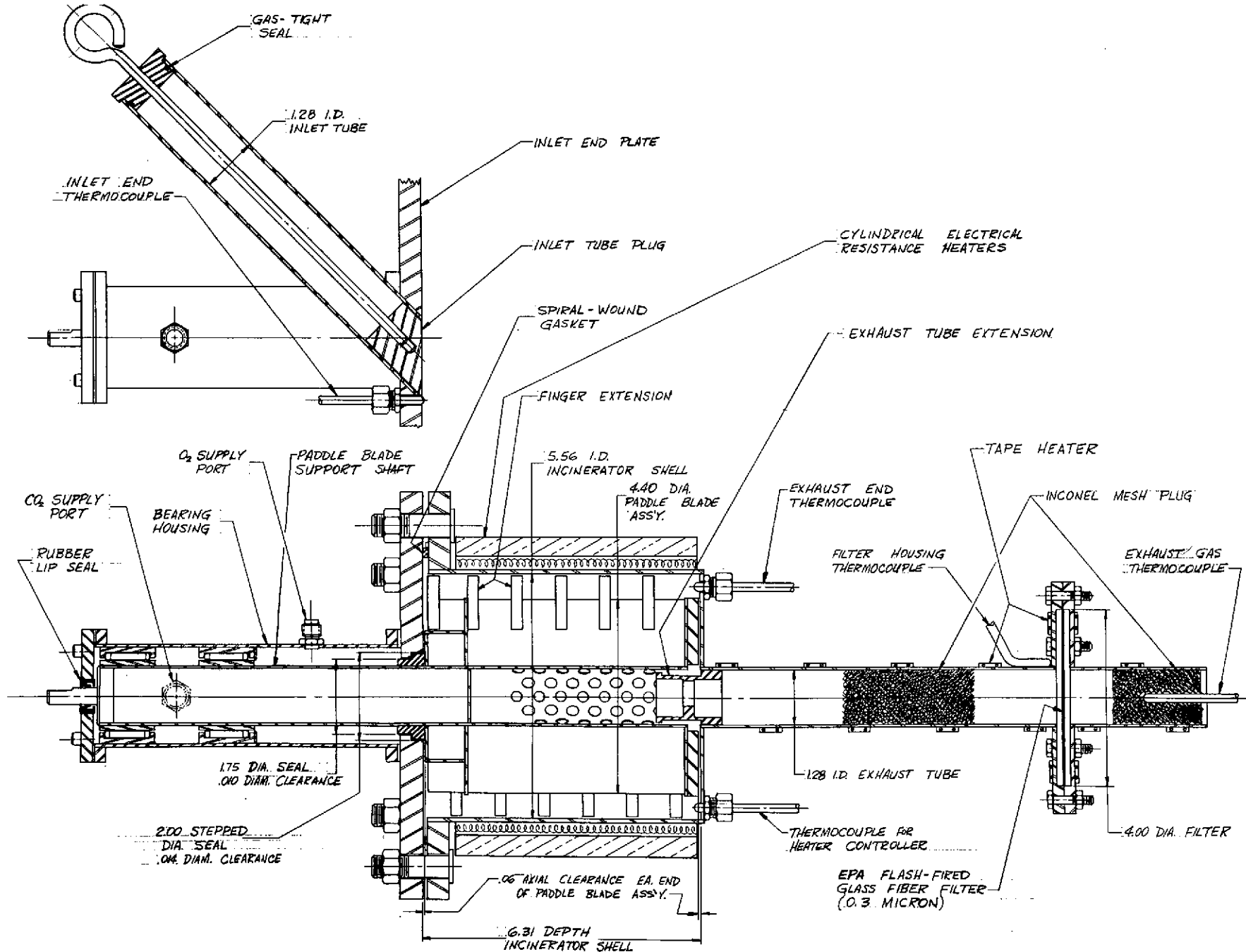


Figure 12. INCINERATOR CONFIGURATION FOR INCINERATION TEST 5

inlet end plate, (3) reduction in the clearance between the paddle blade assembly and the end plates of the incinerator through the addition of a thicker end plate to the paddle blade assembly, (4) an extension of the fixed exhaust tube into the incinerator, and (5) thicker paddle blade assembly "finger" extensions. In addition, the bearing housing gas flow rate was increased, and carbon dioxide was used in place of air to provide an inert atmosphere. To prevent plugging of the oxygen supply tube with wastes, oxygen was supplied through the bearing housing rather than through the inlet tube. Finally, a thermocouple was mounted in the inlet end plate of the incinerator to provide additional monitoring of the incinerator temperature.

The objectives of the fifth incineration test were to: (1) verify that thicker "finger" extensions will not bend, (2) verify that leakage into the bearing housing and the exhaust tube can be prevented by the use of suitable seals, (3) verify that smoke-off is eliminated when the inlet tube is fully plugged after loading, (4) determine accurate oxygen requirements, and (5) determine the amount of particulate matter entrained in the exhaust gases.

The incineration test was run with the rotating-paddle incinerator loaded with approximately three quarters (by weight) of the load used in the previous four tests. A smaller load was used to reduce the possibility of liquid waste leakage into the exhaust tube and bearing housing and also to make the total weight of the solids contained in the waste load approximately the same as for the previous tests. (The urine distillate residue used for this test contained 65.4% solids while for the previous four tests it contained 45.6% solids.)

The paddle blade assembly was run initially at a rotational speed of 300 rpm. During pyrolysis its rotational speed was increased to 400 rpm to counteract the effects of occasional metal-to-metal contact within the new

seal between the paddle blade assembly support shaft and the incinerator inlet end plate of the incinerator. This rotational speed was maintained throughout the remainder of the incineration cycle and also during cool-down.

The carbon dioxide flow rate through the bearing housing was maintained at 800 ml per minute during boil-off, 500 ml per minute during pyrolysis, and 200 ml per minute thereafter. As during the previous test, the incinerator was heated during the processes of boil-off and pyrolysis to a temperature of 540°C (1000°F). The heaters were then turned off, and oxygen was bled at the usual rate of one liter per minute through the bearing housing. A total of approximately 56.6 liters (2 standard cubic feet) of oxygen was supplied. To prevent condensation, the exhaust tube and filter housing were maintained at a temperature of 425°C (800°F) throughout the test and during the initial portion of cool-down.

The following observations were made during the course of the test. First, the temperature of the inlet end plate of the incinerator lagged significantly behind the temperature of the incinerator proper. [The temperature of this end plate remained between 315°C (600°F) and 370°C (700°F) during introduction of oxygen into the incinerator.] This lag in temperature was undoubtedly due to the difference in the thicknesses of this end plate [1.27 cm (1/2 in)] and the rest of the incinerator shell [0.16 cm (1/16 in)] and to the fact that heaters were not in direct contact with the end plate. Second, the incinerator temperature increased steadily during the introduction of oxygen from 540°C (1000°F) to 620°C (1150°F) and then decreased from that point on. Coincident with the incinerator temperature attaining 620°C (1150°F), the filter housing temperature increased rapidly from 425°C (800°F) to approximately 590°C (1100°F) and then decreased again. All of this took place when 53.8 liters (1.9 standard cubic feet) of oxygen had been supplied to the incinerator.

Disassembly of the incinerator after cool-down led to the following observations, many of which are illustrated in Figures 13-15. The ash contained within the incinerator proper (52 grams, see Figure 13) was primarily in the form of fine, light brown powder. This ash was deposited mostly in the center of the incinerator corresponding to the region in which the paddle blade assembly "finger" extensions had broken off during the course of the test (see Figure 14). Of the twenty-three "finger" extensions, twelve had been increased in thickness from 0.08 cm (0.031 in) to 0.16 cm (0.062 in) prior to this test to prevent them from bending. The condition of these "finger" extensions after testing was essentially the same as before testing. However, the remaining thinner "finger" extensions [0.079 cm (0.031 in) thick] were all broken off except for two, one of which was bent at 90°.

The initial portion of the fixed exhaust tube (see Figure 13) contained a small amount of ash (4 grams) similar to that found within the incinerator proper. The paddle blade assembly was also coated with similar ash (4 grams). The filter (see Figure 15) contained very fine ash (1 gram), which was both black and brown. The inlet end plate of the incinerator was well coated with material (8 grams), some of which was in the form of light brown powder and some of which was black and hardened. (This coating was undoubtedly due to the temperature lag discussed earlier.)

Finally, a small amount (2 grams) of loose black material was found within the bearing housing adjacent to the new seal. This material appeared to be metallic when broken; it was later found to be highly magnetic. It was concluded that this material had been produced by metal rubbing on metal within the seal region. The bearing housing itself appeared to have had no contact with the wastes themselves.

The results of this test led to the following conclusions:

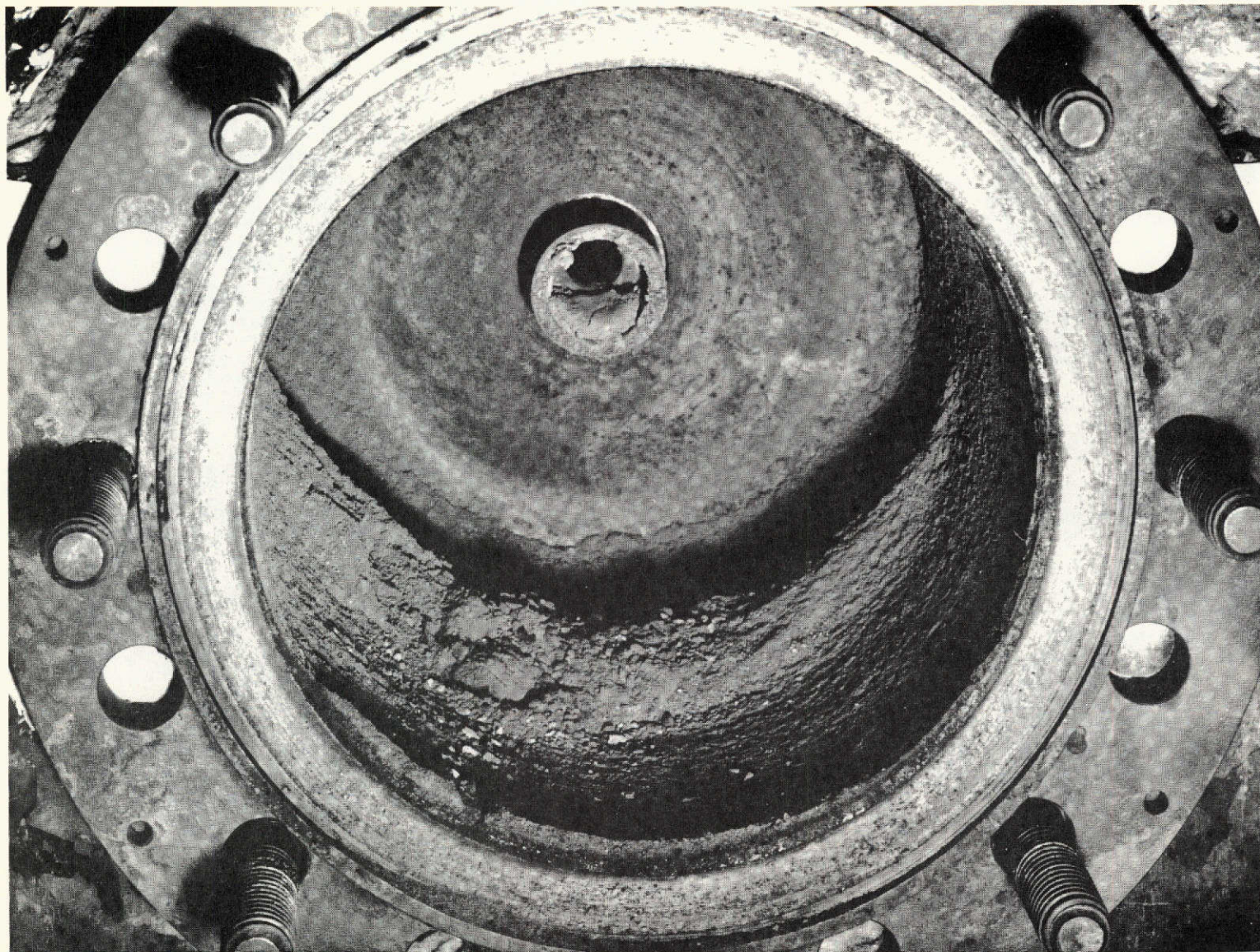


Figure 13. RESULTS OF INCINERATION TEST 5: PHOTOGRAPH OF INCINERATOR SHELL
SHOWING FINAL ASH AND ASH ACCUMULATION IN EXHAUST
TUBE EXTENSION INTO INCINERATOR

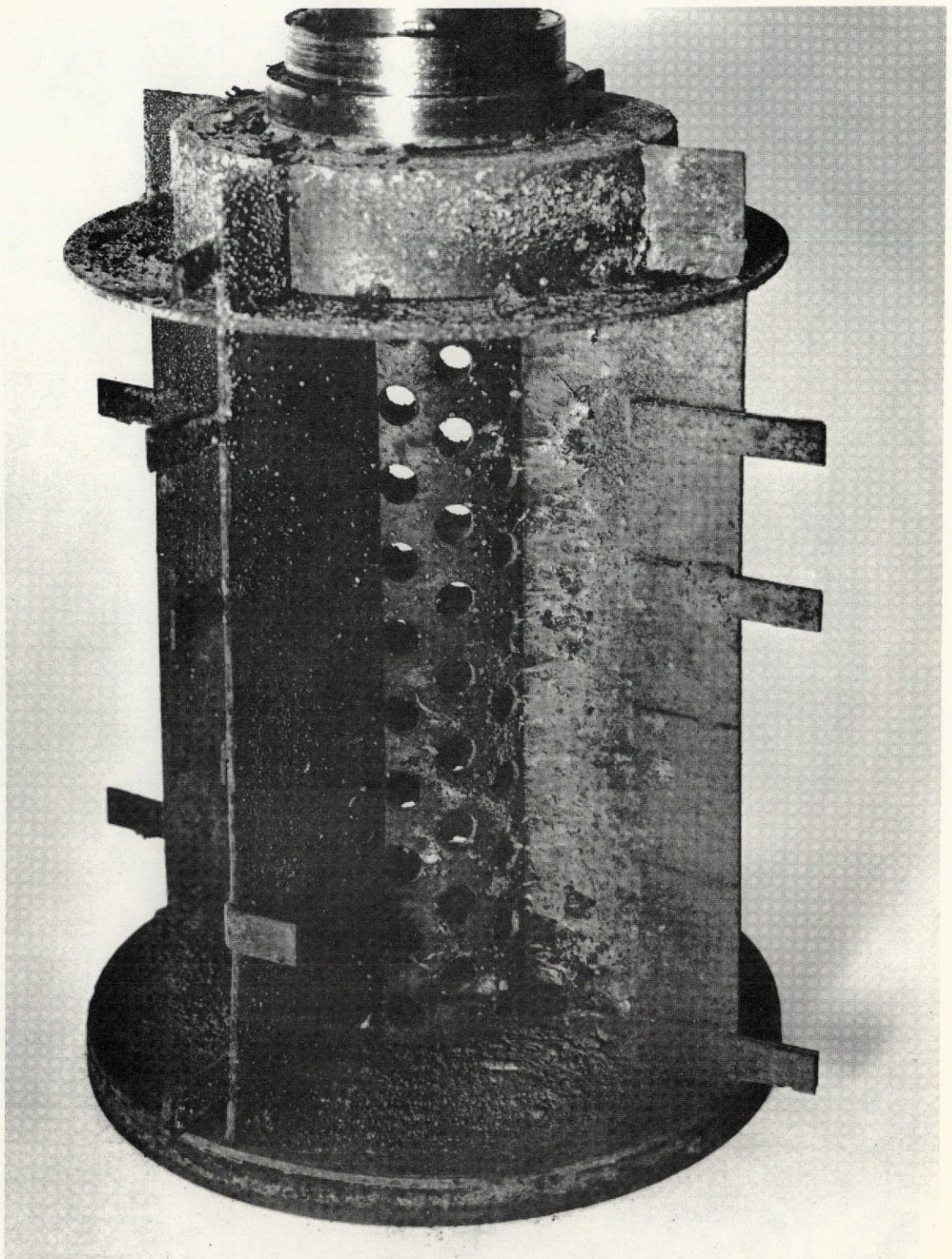


Figure 14. RESULTS OF INCINERATION TEST 5: PHOTOGRAPH OF
PADDLE BLADE ASSEMBLY SHOWING FINAL
CONDITION OF FINGER EXTENSIONS

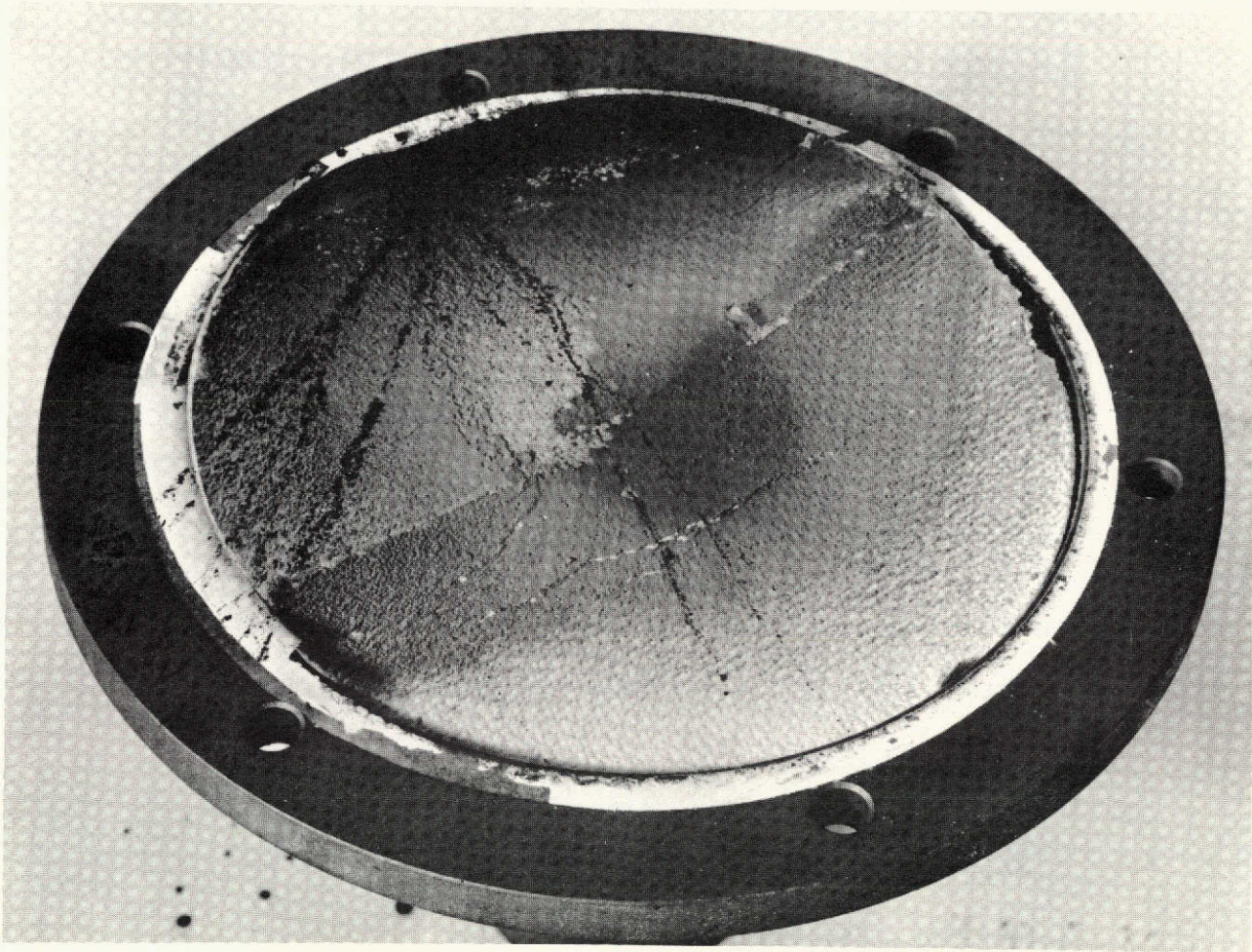


Figure 15. RESULTS OF INCINERATION TEST 5: PHOTOGRAPH OF
INCINERATOR SIDE OF EXHAUST TUBE FILTER
SHOWING BUILD-UP OF FINE PARTICULATES

1. "Finger" extensions that are 0.16-cm (0.062-in) thick are apparently strong enough not to undergo permanent bending.
2. Leakage into the bearing housing and exhaust tube can be prevented through the use of the present seal arrangements.
3. The type of smoke-off observed during pyrolysis on previous tests can be prevented by fitting the inlet tube with a plug after waste loading such that wastes cannot remain or build up there.
4. Approximately 53.8 liters (1.9 standard cubic feet) of oxygen are required for the type of waste load used on this test.
5. A significant amount of particulate matter is entrained in the exhaust gases (equivalent to the ash found in the exhaust tube and on the filter after this test), although this amount is considerably less than the results of previous tests seemed to indicate.
6. The basic objectives of this test were all achieved, and further testing of the incinerator prior to design of an integrated subsystem was not performed.

3.3.2 Simulated Ash Removal Tests

A series of tests was run using the plastic model incinerator (see Figure 1) to determine the extent of final ash adhesion on the incinerator walls and to study the feasibility of ash removal from the incinerator by reverse flushing with air. Tests conducted during the previous program (NASA Contract No. NAS 2-5442, GARD Project 1493) revealed that the final ash remaining after incineration adhered slightly to the incinerator walls and had to be physically dislodged; however, the component arrangement in this system did not permit adequate distribution of oxygen into the waste mass.

To the original plastic model incinerator (i e., paddle blades without "finger" extensions), 100 grams of finely ground salt crystals (simulated final ash) were introduced. The paddle blades were rotated at 400 rpm with the model incinerator in both the vertical and horizontal orientation. A shop vacuum cleaner was used to reverse flush air through the incinerator. Little or no movement of the salt crystals was observed in either orientation.

In a second test, approximately 140 grams of actual ash from incineration Test 1 was ground into powder more characteristic of later incineration tests using a mortar and pestle. This ash was introduced into the plastic model incinerator while mounted in the horizontal orientation with the waste inlet tube in the same horizontal plane as the rotational axis of the incinerator. The paddle blade assembly (now fitted with "finger" extensions) rotational speed was maintained at 300 rpm. As before, a shop vacuum cleaner was used to reverse flush air through the incinerator (at a rate of 40 cubic feet per minute as measured with a vane anemometer). Most of the ash was readily removed from the incinerator with a small quantity remaining undisturbed at the bottom of the incinerator. This remaining ash was not removed even after the inlet tube had been rotated 90° to position it at the bottom of the incinerator.

Upon disassembly of the plastic model incinerator, the remaining ash was collected and found to have a mass of 14 grams, or 10% of that initially placed within the unit. It is anticipated that this residual amount of ash is acceptable within an actual incinerator between incineration cycles.

3.3.3 Liquid Containment Tests

While incineration tests with the rotating-paddle incinerator had established its liquid containment capabilities in the horizontal orientation, such information was not available for the vertical orientation. The plastic model

incinerator was therefore tested in the vertical orientation with water to determine maximum liquid volume as a function of paddle blade assembly rotational speed. Maximum liquid volume was determined by observing the onset of leakage out the central exhaust tube in the bottom end plate of the incinerator shell. Test results are shown in Figure 16, together with a theoretical curve for steady-state rotation of water for such a configuration (with friction accounted for at the cylindrical walls of the container).

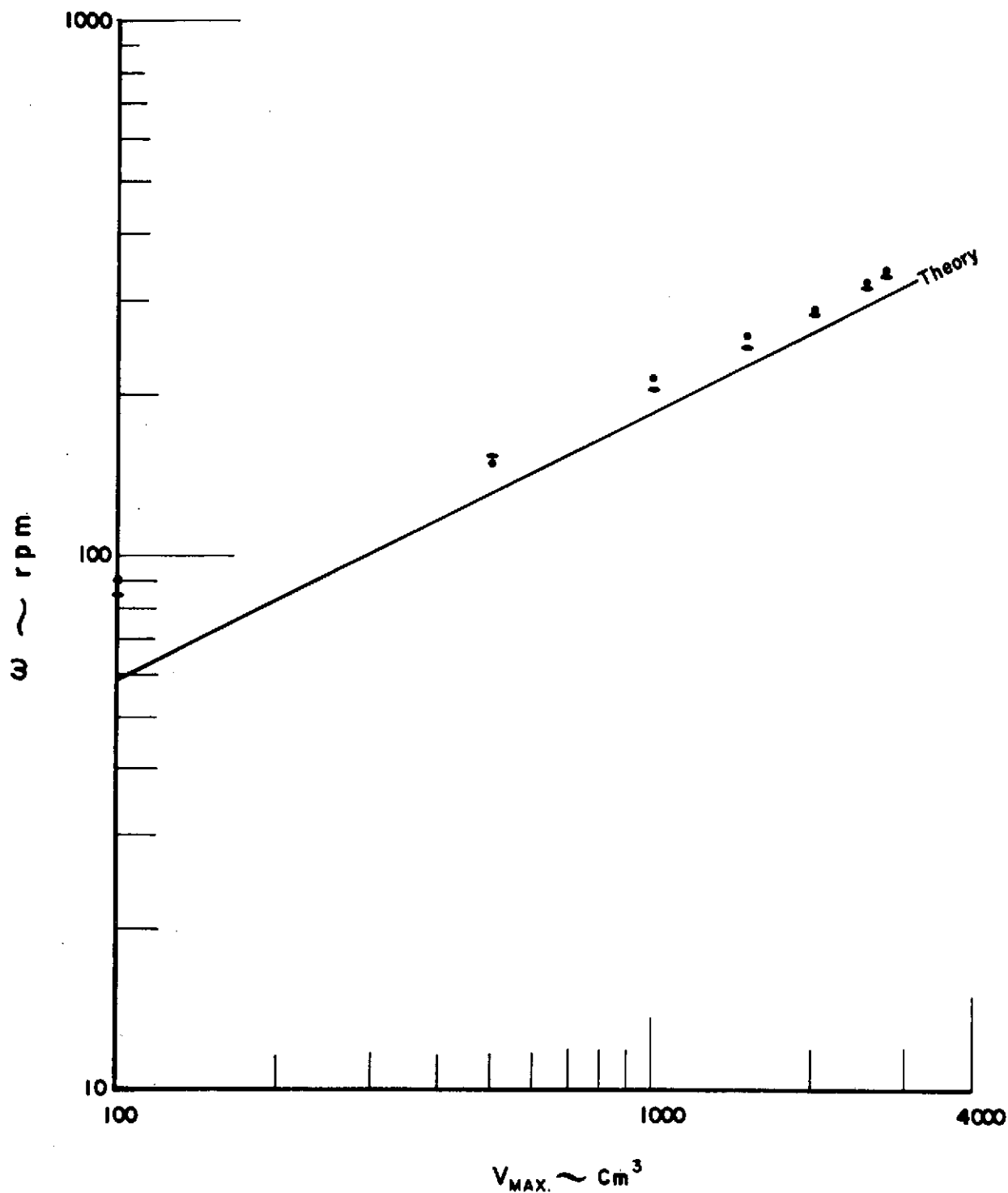


Figure 16. MAXIMUM INCINERATOR LIQUID VOLUME AS A FUNCTION OF PADDLE BLADE ASSEMBLY ROTATIONAL SPEED - WATER ONLY, PLASTIC MODEL INCINERATOR

Section 4

CONCLUSIONS AND RECOMMENDATIONS

4.1 Conclusions

On the basis of the investigations, studies, and tests conducted during Task I of this program, the following conclusions have been reached concerning the components comprising a dry incineration waste management subsystem.

1. A shear bar, positioned on the inside of the incinerator inlet cover plate and located on a chord between the rotating paddle drive shaft and the pneumatic waste transport tube, in contact with the rotating paddles, is the most effective of the particle size reduction mechanisms evaluated.

2. The "scissors" action created by the rotating paddles/shear bar arrangement effectively reduces the size of dry and wet toilet tissue as well as simulated human wastes to allow their passage into the incinerator.

3. Little or no accumulation of wastes around the waste transport tube inlet to the incinerator results from the use of this configuration.

4. Paddle blade/shear bar contact is only required (and desired) during waste loading of the incinerator.

5. The final component configuration should include an indexing mechanism to allow movement of the paddle blade assembly axially such that metal-to-metal contact between the shear bar and paddle blades takes place during waste loading of the incinerator but not during all other incinerator operations.

6. A paddle blade assembly rotational speed of 300 rpm is sufficient to cut adequately all waste materials against the shear bar.

7. Pneumatic drag of whole wastes from a collection site (commode) to the rotating-paddle incinerator, with subsequent size reduction of these wastes within the incinerator, is the most effective method of waste transport.

8. The pneumatic drag is best created by a blower located downstream of the system with the transport gas recycled to the collection site (commode).

9. A minimum inside diameter of 6.4 cm (2-1/2 in) for the waste transport tube is required to accommodate adequately whole fecal matter and toilet tissue.

10. The use of a special disposable paper liner within the transport tube, with subsequent release of the liner to the incinerator after each use, is the most effective method evaluated for keeping the inside walls of the tube clean.

11. Of the candidate liner materials tested, four meet all design criteria, and six others appear suitable for use, if necessary.

12. Four paddle blades, located 90° apart on a central rotating tube and extending the entire length of the incinerator, are required to retain all wastes properly within the incinerator.

13. Similarly, a minimum paddle blade rotational speed of 300 rpm is required to create a sufficient centrifugal force field for retainment purposes.

14. The use of a series of "finger" extensions on each paddle blade that come to within 0.13 cm (0.05 in) of the incinerator wall is sufficient to prevent ash adhesion on the incinerator wall during dry incineration of the wastes.

15. The "fingers" continuously "rake" through the waste mass to:

- a. Reduce the size of the wastes,
- b. Prevent localized build-up of the wastes, and
- c. Continually expose more waste surface for thermal processing and oxidation.

16. "Finger" extensions of a suitable thickness and material are required to prevent physical bending of the "fingers" under high thermal and mechanical stresses.

17. "Finger" extensions made from 0.16-cm (0.062-in) thick Hastelloy-X have enough strength to resist permanent bending at temperatures up to 650°C (1200°F).

18. Transport and generated gases and vapors can exhaust properly from the incinerator through holes in the wall of the central rotating tube located between each paddle blade.

19. The use of knitted wire mesh over these holes to prevent the escape of stray waste particles is neither necessary nor desirable.

20. A plug/seal, fitted within the waste transport tube after waste loading and made flush with the inner surface of the incinerator cover plate, is necessary to prevent wastes from accumulating inside this tube.

21. A labyrinth seal, supplied with an inert gas at a slight positive pressure, and located around the rotating paddle drive shaft at the incinerator cover plate, effectively prevents the passage of transport and generated gases and waste materials into the bearing housing.

22. Use of carbon dioxide to keep the bearings cool and the labyrinth seal clean is desirable and satisfactory.

23. Extending the fixed exhaust tube into the central rotating tube and reducing the clearance between the end plate of the rotating paddle blade assembly and the end plate of the incinerator to the minimum feasible effectively reduces the amount of waste materials discharged into the exhaust tube.

24. Heaters are required on both end plates of the incinerator to eliminate the temperature lag experienced without these heaters.

25. Oxygen for the combustion phase of waste processing is best distributed within the incinerator when admitted to the bearing housing and allowed to flow through the labyrinth seal into the incinerator.

26. An oxygen flow into the incinerator of one liter per minute is sufficient to oxidize all waste materials with minimum expended oxygen.

27. Approximately 28.3 liters (1 standard cubic foot) of oxygen is required for the final combustion phase of processing the daily solid waste production from one man combined with an equal quantity of urine distillate residue and small amounts of toilet tissue and commode rinse water.

28. Filtering of the exhaust gases and vapors emanating from the incinerator is required. While the particulates entrained in the exhaust flow can be adequately filtered using a glass-fiber filter, long-term use of such filtering is undesirable because of replacement requirements. It would be more desirable to use the catalytic afterburner itself for such purposes. It remains to be demonstrated, however, that the catalytic afterburner can be used in this fashion while adequately satisfying its other performance requirements.

29. The catalytic afterburner developed in the previous program (NASA Contract No. NAS 2-5442, GARD Project 1493) is of suitable size and configuration for use in an integrated subsystem with only minor design modifications (see Section 5).

30. Removal of ash from the incinerator can be adequately achieved by reverse flushing with air.

4.2 Recommendations

Based on the observations and conclusions drawn from Task I of the program, a series of recommendations have been made concerning the use, operation, fabrication, evaluation, and future testing of an integrated zero-g pneumatic transporter/rotating-paddle incinerator/catalytic afterburner subsystem for processing human wastes on board spacecraft. These recommendations have been put in the form of an operational specification for a baseline integrated subsystem; this specification is presented in Section 5.

Section 5

BASELINE INTEGRATED WASTE INCINERATION SUBSYSTEM

Based on the results of the current program and on the conclusions drawn from these results, an operational specification for a baseline integrated waste incineration subsystem has been prepared. The operational specification has been divided into categories similar to those used for the individual component specifications discussed in Section 2. These categories include purpose, mode of operation, configuration, performance requirements, operating constraints, sequence of operations, and primary specifications. The operational specification is presented in Section 5.1.

Prior to preparing the operational specification, a number of sizing calculations were performed to ensure that the baseline subsystem will be capable of processing, on a cyclic basis, the typical daily waste load anticipated from six men:

Human Feces (25% solids)	900 grams	(2.0 pounds)
Urine Distillate Residue (50% solids)	900 grams	(2.0 pounds)
Rinse Water	320 grams	(0.7 pounds)
Toilet Tissue and Liners	<u>45 grams</u>	<u>(0.1 pounds)</u>
TOTAL WEIGHT	2165 grams	(4.8 pounds)

(This is approximately twice the waste load processed during most of the incineration tests conducted previously.)

These sizing calculations were aimed at specifically ensuring that:

1. The incinerator will be capable of properly containing and confining the waste load [approximate volume of the raw waste load: less than 2.8 liters (0.1 cubic foot)].

2. The incinerator shell surface area will be large enough to allow processing the wastes in approximately the same amount of time as required during incineration tests conducted previously, with essentially the same waste load and heat input per unit of shell surface area.

3. The catalytic afterburner will be large enough to allow processing of the gases and vapors which exhaust from the incinerator at the flow rates implied by Item 2.

To satisfy these requirements, the incinerator has been designed with a shell surface area approximately twice that of the previous incinerator. It has also been verified, based on the results of the previous program, that GARD's existing catalytic afterburner is capable of operating successfully with gas and vapor flow rates of the order of 56.6 liters (2 cubic feet) per minute (flow rates of this order are expected during boil-off).

5.1 Operational Specification

5.1.1 Purpose

The baseline integrated waste incineration subsystem shall collect, transport, and convert solid and liquid human wastes into innocuous, sterile end products. It shall be capable of processing, on a cyclic basis, the typical daily waste load anticipated from six men:

Human Feces (25% solids)	900 grams	(2.0 pounds)
Urine Distillate Residue (50% solids)	900 grams	(2.0 pounds)
Rinse Water	320 grams	(0.7 pounds)
Toilet Tissue and Liners	<u>45 grams</u>	<u>(0.1 pounds)</u>
TOTAL WEIGHT	2165 grams	(4.8 pounds)

5.1.2 Mode of Operation

Human wastes shall be collected in a waste transport tube fitted with a disposable liner and transported pneumatically to an incineration unit in which the solid wastes shall be physically reduced in size and the entire waste mass converted to vapors, gases, and an inorganic ash.

The wastes -- including the liner and used toilet tissue -- shall be retained within the incinerator through the action of an artificial force field created by a rotating paddle arrangement within the incinerator. All transport and generated gases and vapors shall be discharged from the central rotational axis.

Conversion of the wastes shall take place in three steps as follows:

1. Boil-off of volatiles and water by heating from ambient temperature through 100°C (212°F),
2. Pyrolysis (thermal destruction in the absence of oxygen) of the dehydrated residue by heating from 100°C (212°F) to 540°C (1000°F), and
3. Final combustion with oxygen of the carbonaceous pyrolysis residue at 540°C (1000°F) to 650°C (1200°F).

The generated gases and vapor shall pass first through a catalytic afterburner maintained at 370-480°C (700-900°F) for further processing with oxygen and then through a condenser for the collection of all condensible vapors. The final inorganic ash shall be removed from the incinerator to storage by reverse air flow through the incinerator into an ash collector.

5.1.3 Configuration

The baseline integrated subsystem configuration shall be as depicted in Figure 17. The subsystem shall consist of a waste transport tube, incineration unit, catalytic afterburner, oxygen controller, condenser, blowers, and

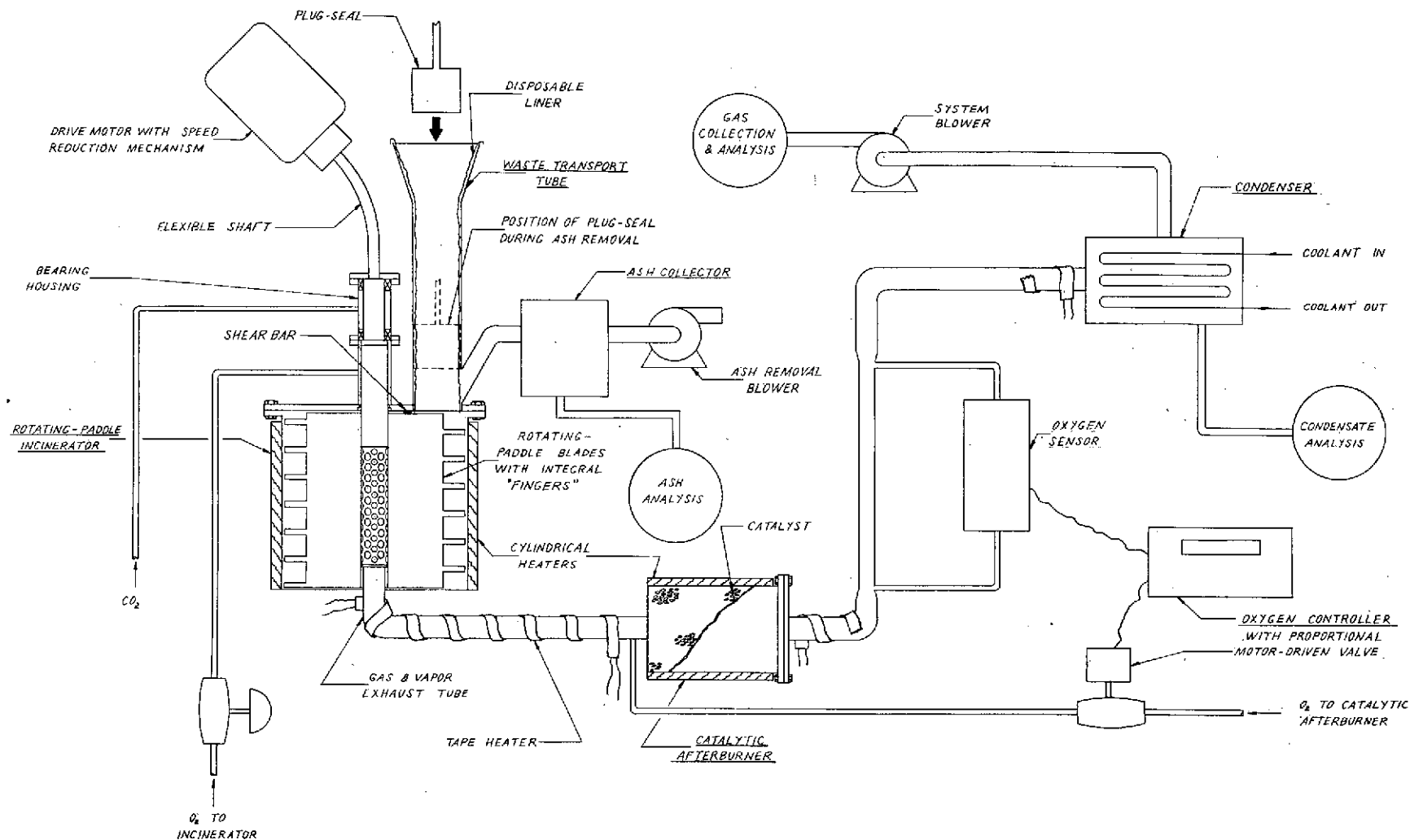


Figure 17. BASELINE INTEGRATED WASTE INCINERATION SUBSYSTEM

necessary interconnecting piping, valves, thermocouples, gauges, controls, wiring, and insulation for proper operation of the subsystem.

Waste Transport Tube - The waste transport tube shall be cylindrical -- 6.4-cm (2-1/2-in) ID, 30.5-cm (12-in) length, stainless steel -- and fitted at its inlet end with an 11.4-cm (4-1/2-in) diameter stainless steel waste acceptance funnel. The tube and funnel shall be fully lined with a suitable disposable liner material exhibiting the following features:

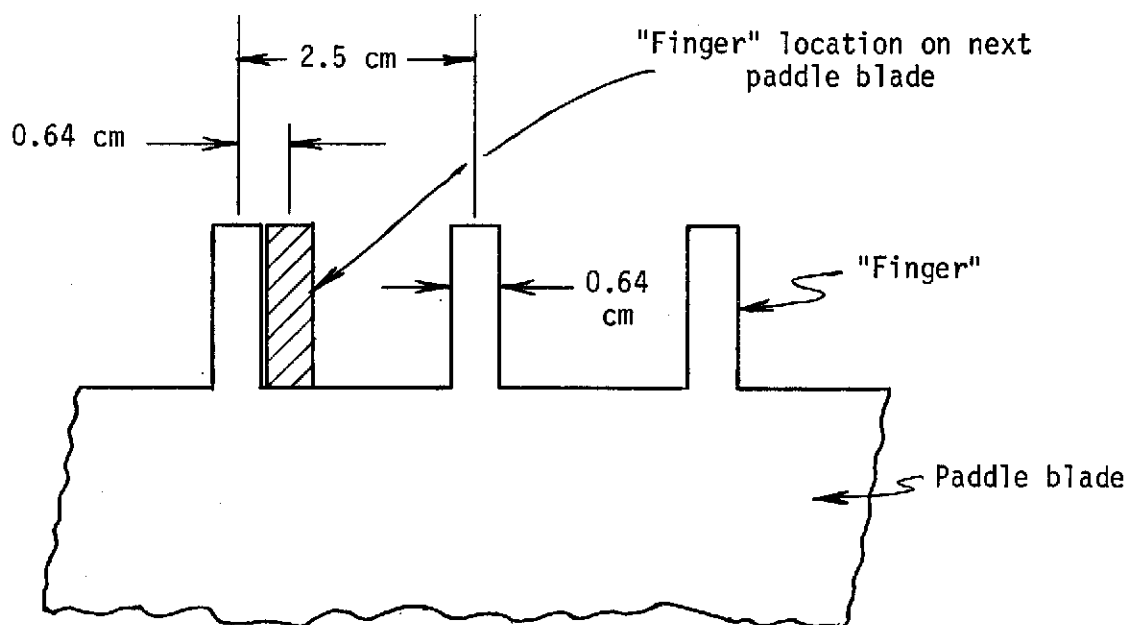
- Nonabsorbent (water-resistant or water-repellent)
- Resistant to oils and greases
- Easily torn or shredded
- Combustible with no objectionable off-gases
- Lightweight and flexible

The waste transport tube shall be permanently attached to the incinerator and shall accept a Hastelloy-X plug to seal the waste transport tube during processing of the wastes. This plug/seal shall be inserted into the tube inlet manually after the collection of a waste load.

The waste transport tube shall also be fitted with a 1.9-cm (3/4-in) ID stainless steel take-off tube located at the intersection of the waste transport tube and the incinerator and positioned 30° to the waste transport tube axis to provide for final ash removal from the incinerator.

Incineration Unit - The incineration unit shall be a cylindrical shell -- 20.6-cm (8-1/8-in) OD, 21.6-cm (8-1/2-in) length, 0.16-cm (0.063-in) wall thickness, Hastelloy-X -- fitted externally with cylindrical electrical resistance heaters and embedded within suitable insulation. The waste transport tube shall be attached to the incinerator on the main detachment flange adjacent to the incinerator wall and parallel to its central axis.

The inner volume of the incinerator shall contain a rotating assembly consisting of a 3.5-cm (1-3/8-in) OD Hastelloy-X central tube located along the axis of the incinerator and fitted with four 0.24-cm (0.093-in) thick Hastelloy-X paddle blades; these blades shall be permanently attached along the length of the tube and shall be at right angles to each other. Each paddle blade shall be 6.4 cm (2-1/2 in) wide and fitted along its outermost edge with seven 0.64-cm (1/4-in) wide "fingers", which shall extend to within 0.16 cm (1/16 in) of the inside wall of the incinerator. The "fingers" shall be made integral with the paddle blades and shall be positioned 2.5 cm (1 in) apart on a blade and 0.64 cm (1/4 in) from the adjacent "finger" on the next blade as depicted in the following drawing.



Within the incinerator, the central rotating tube shall contain a large number of 0.64-cm (1/4-in) diameter holes through its wall to permit discharge of the transport and generated gases. This tube shall be rotated by an external 1/2-horsepower electrical motor fitted with a flexible drive shaft to

provide a maximum paddle blade rotational speed of 350 rpm. The rotational drive shaft shall be common with the central tube and shall be contained within two roller bearings located within a sealed housing attached to the main detachment flange of the incinerator. The drive shaft/central tube shall penetrate the main detachment flange of the incinerator through a labyrinth seal having clearance gaps of 0.013 cm (0.005 in) or less.

The incinerator end plate shall be 0.24-cm (0.093-in) thick Hastelloy-X and fitted at its center with a 2.5-cm (1-in) OD Hastelloy-X gas and vapor exhaust tube. This tube shall penetrate into the center of the rotating central tube for a maximum distance of 7.6 cm (3 in); it shall not touch the rotating tube. The opposite end of this exhaust tube shall be connected to the inlet end plate of the catalytic afterburner; the overall length of the tube shall not be less than 10.2 cm (4 in) or more than 15.2 cm (6 in). The exhaust tube shall be wrapped with an electrical tape heater and embedded within suitable insulation.

The main detachment flange of the incinerator shall be 0.64-cm (1/4-in) thick Hastelloy-X and bolted to the incinerator shell; a spiral-wound stainless steel/asbestos gasket shall be used to seal this flange. A Hastelloy-X cutting mechanism shall be provided within the incinerator at the intersection of the waste transport tube and the main detachment flange.

Catalytic Afterburner - The catalytic afterburner shall be a cylindrical shell -- 9.5-cm (3-3/4-in) OD, 16.5-cm (6-1/2-in) length, 0.08-cm (0.032-in) wall thickness, Hastelloy-X -- fitted externally with cylindrical electrical resistance heaters and embedded within suitable insulation. It shall contain approximately 1200 gm (2.65 lb) of catalyst consisting of 0.32-cm (1/8-in) diameter by 0.32-cm (1/8-in) long cylindrical alumina pellets coated with 0.5% palladium. Hastelloy-X fine mesh screens shall be fitted above and below the catalyst bed to prevent loss of the catalyst.

The catalytic afterburner shall be fitted with a 0.64-cm (1/4-in) thick Hastelloy-X detachment flange fitted at its center with a 1.9-cm (3/4-in) OD Hastelloy-X exhaust tube, which shall be connected at its other end to a condenser. This exhaust tube shall contain two tee's to provide a 1.0-cm (3/8-in) OD Hastelloy-X gas sample line. The sample line shall pass through a Thermo-Lab "Thermox" WDG Oxygen Sensor to monitor the oxygen concentration of the final exhaust gas. The signal from the sensor shall go to a Thermo-Lab "Thermox" WDG Analyzer, whose amplified signal shall go to an API Model 228-21 Double Output, 2-Mode Controller. This controller shall signal an API Model 5001 Current/Position Converter, which shall operate a Barber-Coleman Proportional Motorized Operator, which, in turn, shall drive an oxygen valve feeding oxygen to the catalytic afterburner.

Other Components - Other components in the subsystem shall include a condenser and a properly sized blower located downstream of the condenser. This blower shall provide the necessary air flow for pneumatic transport of the waste materials into the incinerator and shall provide for continuous removal of vapors and gases generated during processing of the wastes.

A second blower shall be provided for the removal of the final inorganic ash from the incinerator. This blower shall be located downstream of an ash collector attached to the ash removal tube previously described.

Miscellaneous components shall include, but shall not be limited to, thermocouples, recorders, temperature controllers, pressure/vacuum gauges, and flow meters.

5.1.4 Performance Requirements

Waste Transport Tube

- Must accept whole fecal matter and used toilet tissue and allow pneumatic transport of these materials to the incinerator.

- Must not physically plug with wastes
- Must not allow isolated stray waste particles to collect outside of the liner
- Must be easily cleaned after use or kept clean during use

Incineration Unit

- Must reduce size of whole waste materials and protective liner to be readily accepted by rotating paddle blades
- Must confine all liquids and solids within the annular space between the inside wall and the rotating paddle blades
- Must completely reduce wastes to vapors, gases, and an inorganic ash
- Must completely sterilize all waste particles
- Must accept pneumatic transport gas flow
- Must allow for complete discharge of transport and generated gases and vapors without the loss of liquid or solid particles
- Must not leak solids, liquids, or gases into drive tube housing
- Must allow for adequate removal of the final inorganic ash by reverse air flow
- Must provide for adequate oxygen distribution during final combustion step

Catalytic Afterburner

- Must accept flow rate of transport and generated gases and vapors
- Must oxidize all unoxidized gases and vapors
- Must physically filter any entrained particulates from the incinerator exhaust gas

- Must provide sterilization of low-temperature volatiles and water vapor

5.1.5 Operating Constraints

Waste Transport Tube

- Must operate between waste acceptance funnel at ambient temperature and incinerator up to 650°C (1200°F)
- Transport gas flow must entrain all waste materials and transport them to the incinerator with no detrimental build-up of back pressure and no contamination of tube walls
- Transport gas flow rate must be minimum feasible

Incineration Unit

- Must operate between ambient temperature and 650°C (1200°F)
- Must exhaust all transport and generated gases and vapors to catalytic afterburner
- Must not drive gases and vapors back into waste transport tube or into bearing housing
- Must accept whole waste materials and adequately reduce their size
- Must operate under both reducing and oxidizing atmospheres

Catalytic Afterburner

- Must operate continuously at 370-480°C (700-900°F)
- Must prevent generated gases and vapors from short-circuiting through the catalyst bed
- Must operate continuously under a strong oxidizing atmosphere

5.1.6 Sequence of Operations

During operation of the waste incineration subsystem, the following operations will be performed continuously:

- Rotation of the entire paddle blade assembly
- Bleeding of an inert gas (carbon dioxide) into the bearing housing at a prescribed flow rate for cooling of the bearings and positive pressure differential across the labyrinth seal
- Heating of the catalytic afterburner to 370-480°C (700-900°F)
- Heating of the exhaust tubes to a minimum of 260°C (500°F)
- Monitoring of the oxygen concentration of the exhaust gas from the catalytic afterburner and maintaining a minimum of 5% oxygen in this gas
- Operation of the transport and vapor removal blower
- Operation of the downstream vapor condenser

Upon activation of the entire integrated subsystem, a preformed disposable liner will be inserted into the waste transport tube and clamped in place at the waste acceptance funnel inlet. Whole wastes and toilet tissue will be deposited in the funnel and pneumatically transported into the incinerator where they will be reduced in size by the cutting mechanism. The macerated wastes will then be distributed uniformly within the annular region between the rotating paddle blades and incinerator wall. The "fingers" will continuously rake through the waste mass to keep it from sticking and caking on the incinerator wall.

After the addition of wastes equivalent to that generated daily by six men, the prescribed amount of urine distillate residue and rinse water will be supplied through the waste transport tube. The disposable liner will then be released, and the plug/seal brought into position.

The incinerator heaters will then be activated at the prescribed power input to begin the thermal reduction process. When the waste mass remaining in the incinerator attains a temperature of 540°C (1000°F) as sensed by a thermocouple, the incinerator heaters will be shut off, and oxygen will be admitted at a prescribed flow rate to the bearing housing, downstream of the bearings. When all oxidizable materials have been oxidized within the incinerator, the oxygen concentration in the final exhaust gas will increase, and the oxygen controller will shut all heaters and all oxygen flows off. After the necessary cool-down, the ash removal blower will then be activated, and the plug/seal will be positioned to clear the opening to the ash removal tube; ash will then be "vacuumed" from the incinerator for a prescribed period of time, after which the entire subsystem will be shut down.

5.1.7 Primary Specifications

<u>Waste Transport Tube:</u>	6.4 cm (2-1/2") ID x 7.0 cm (2-3/4") OD x 30.5 cm (12") long, 316 L S.S.
<u>Waste Acceptance Funnel:</u>	Tapered, 11.4 cm (4-1/2") dia. x 6.4 cm (2-1/2") dia. x 10.2 cm (4") long, 316 L S.S.
<u>Plug/Seal:</u>	6.4 cm (2-1/2") dia. x 6.4 cm (2-1/2") long, Hastelloy-X
<u>Liner Material:</u>	20# White #83600 M.G. Kraft with 4# Waysorb (Thilmany Paper Company) or equivalent
<u>Cutting Mechanism:</u>	Shear bar, 0.64 cm (1/4") wide x 19.4 cm (7-5/8") long, Hastelloy-X

<u>Incinerator Shell:</u>	Cylindrical, 20.6 cm (8-1/8") OD x 0.16 cm (0.063") wall x 21.6 cm (8-1/2") long, Hastelloy-X
<u>Incinerator Exhaust End Plate:</u>	20.6 cm (8-1/8") dia. x 0.24 cm (0.093") thick, Hastelloy-X
<u>Incinerator Main Detachment Flange:</u>	29.8 cm (11-3/4") dia. x 0.64 cm (1/4") thick, Hastelloy-X
<u>Incinerator Flange Bolts:</u>	1.0 cm (3/8")-16NC x 2.5 cm (1") long, 316 S.S. on 22.9 cm (9") b.c.
<u>Central Rotating Shaft/Tube:</u>	3.5 cm (1-3/8") OD x 0.11 cm (0.045") wall, Hastelloy-X
<u>Paddle Blades:</u>	6.4 cm (2-1/2") wide x 20.3 cm (8") long x 0.24 cm (0.093") thick, with 7 integral "fingers", Hastelloy-X (4)
<u>"Fingers":</u>	0.64 cm (1/4") wide x 1.8 cm (11/16") long x 0.24 cm (0.093") thick, inte- gral with paddle blade, Hastelloy-X (28)
<u>Incinerator Heaters:</u>	Model 50821 Quarter Cylindrical (Lindberg Hevi-Duty) around shell (4), Model 50116 Flat (Lindberg Hevi-Duty) on end plates (2)
<u>Incinerator Main Flange Gasket:</u>	Spiral-wound, 316 S.S./asbestos, 20.8 cm (8-3/16") ID x 21.7 cm (8- 17/32") OD (Flexitallic Gasket Co.)

<u>Rotational Drive Motor:</u>	1/2-HP, 1725 rpm, with SCR adjustable speed control, 115 V, 60 Hz (Dayton Manufacturing Company)
<u>Speed Reduction Mechanism:</u>	Model S-133-MC56-5-A "Uniline", right-angle, 5:1 reduction ratio (Ohio Gear Company)
<u>Motor Coupling to Drive Tube:</u>	Model 50FC flexible coupling (Stow Manufacturing Company)
<u>Bearings:</u>	Model JH2016 cylindrical roller bearings (2) (Torrington Manufacturing Company)
<u>Bearing Housing:</u>	Cylindrical, 3.5 cm (1-3/8") ID x 0.16 cm (1/16") wall x 12.7 cm (5") long, 316 L S.S.
<u>Gas Exhaust Tube:</u>	2.5 cm (1") OD x 0.12 cm (0.048") wall, Hastelloy-X
<u>Catalytic Afterburner:</u>	Cylindrical, 9.5 cm (3-3/4") OD x 0.08 cm (0.032") wall x 16.5 cm (6-1/2") long, Hastelloy-X
<u>Catalytic Afterburner Detachment Flange:</u>	12.7 cm (5") dia. x 0.64 cm (1/4") thick, Hastelloy-X
<u>Catalyst:</u>	0.5% palladium on 0.32 cm (1/8") dia. x 0.32 cm (1/8") long cylindrical alumina pellets, 1200 gm (2.65 lb) (Englehard Industries, Inc.)
<u>Catalytic Afterburner Heaters:</u>	Model 50411 Half Cylindrical (Lindberg Hevi-Duty) around shell (2)

Oxygen Concentration Sensing System:

Model WDG "Thermox" sensor, Model WDG "Thermox" analyzer (Thermo-Lab Instruments)

Oxygen Control System:

Model 228-21 double output, 2-mode controller with Model 5001 current/position converter (LFE-API Instruments); Model 35-569 proportional motorized operator (Barber-Coleman); and suitable valve

Condenser (lab only):

Vacuum collection bottles cooled with dry ice/acetone, sized to accept anticipated vapor flow rates

Main Pneumatic Transport & Operational Blower:

Centrifugal-type, sized to accept anticipated gas flow rates

Ash Removal Blower & Ash Collector:

Vacuum cleaner (Kirby Manufacturing Company) or equivalent

Thermocouples:

Model SS-188-K-9 (Claud S. Gordon)

Line Tape Heaters:

Model S-40854-10 (Sargent-Welch Scientific Company)

5.2 Final Design Configuration

Under Task II of this program, the preceding operational specification for a baseline integrated waste incineration subsystem will be translated into detailed design drawings for subsystem fabrication. A working subsystem will then be fabricated and subjected to laboratory testing. The results of this work will be reported separately at the end of Task II.